Spatial and temporal task characteristics as stress: A test of the dynamic adaptability theory of stress, workload, and performance

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ABSTRACT

The goal for this study was to test assertions of the dynamic adaptability theory of stress, which proposes two fundamental task dimensions, information rate (temporal properties of a task) and information structure (spatial properties of a task). The theory predicts adaptive stability across stress magnitudes, with progressive and precipitous changes in adaptive response manifesting first as increases in perceived workload and stress and then as performance failure. Information structure was manipulated by varying the number of displays to be monitored (1, 2, 4 or 8 displays). Information rate was manipulated by varying stimulus presentation rate (8, 12, 16, or 20 events/min). A signal detection task was used in which critical signals were pairs of digits that differed by 0 or 1. Performance accuracy declined and workload and stress increased as a function of increased task demand, with a precipitous decline in accuracy at the highest demand levels. However, the form of performance change as well as the pattern of relationships between speed and accuracy and between performance and workload/stress indicates that some aspects of the theory need revision. Implications of the results for the theory and for future research are discussed.

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1. Introduction

Task induced stress is a ubiquitous phenomenon that can substantially impair an individual's performance, safety, and well-being. Theory and research on human performance under stress have tended to emphasize either the stimulus properties (e.g., temperature, vibration, noise; for recent meta-analytic reviews, see Conway, Szalma, & Hancock, 2007; Hancock, Ross, & Szalma, 2007; Szalma & Hancock, 2011) or physiological mechanisms of response such as the general adaptation syndrome (Selye, 1976) or unitary arousal (Hebb, 1955). However, these single mechanism approaches proved to be insufficient to account for the relationship between stress and performance (Hockey, 1984; Hockey & Hamilton, 1983). The failure of unitary arousal theory in particular led to the development of an energetic resource perspective (Hockey, 1984; 1997; Hockey, Gaillard, & Coles, 1986) in which stress effects result from a person–environment relation that is appraised by an individual as potentially or actually exceeding his/her resources to effectively adapt to the event (Lazarus, 1999; Lazarus & Folkman, 1984).

One of these theories, the Dynamic Adaptability Theory (DAT; Hancock & Warm, 1989), was developed specifically for understanding the mechanisms underlying the effects of stress and workload on adaptive response as it relates to task performance. This theory incorporates both the stimulus and response elements of stress into a single framework, the *trinity of stress* (see Fig. 1). The environmental demands are represented as the *input*, which are the deterministic properties of the task and the immediate physical and social environment that can be specified independent of an individual's response. As most environments impose multiple demands, the input may be viewed as an external demand profile or 'signature' (c.f., Hockey & Hamilton, 1983). Note that for DAT 'input' refers to the demands imposed by the environment (including the task itself), and not only the sensory/perceptual input that is an element of most information processing theories (e.g., Wickens & Hollands, 2000). That is, 'input' in this model reflects each step of the information processing stream (i.e., sensory/perceptual input, the processing requirements of the task, and response options; Wickens & Hollands, 2000). In addition, use of the term 'stress' in Fig. 1 refers to environmental demand rather than the response of the organism (the latter is represented in the other two elements described below). The second component is *adaptation*, which consists of a general (nomothetic) response of the organism to the input. These responses are common to members of the species (e.g., release of stress hormones, mechanisms of arousal, appraisal and coping). Finally, the *output* is the response of the organism that is dependent upon the characteristics of the individual and is

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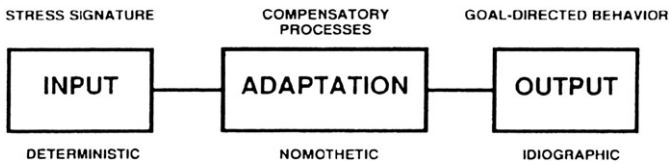 E-mail address: James.Szalma@ucf.edu (J.L. Szalma).

STRESS SIGNATURE   COMPENSATORY PROCESSES   GOAL-DIRECTED BEHAVIOR

INPUT — **ADAPTATION** — **OUTPUT**

DETERMINISTIC   NOMOTHETIC   IDIOGRAPHIC

Fig. 1. The three elements of stress (the 'trinity of stress') incorporated into the dynamic adaptability model (from Hancock & Warm, 1989). *Note.* See footnote 1 regarding use of the term, 'idiographic'.

thus idiographic[1] (e.g., coping strategy selected, appraisal content, levels of arousal or stress hormones). Note that psychomotor response can be either adaptation (e.g., stereotypical responses) or 'idiographic' output (e.g., dependent on skill level).

A fundamental tenet of the dynamic adaptability model is that across a relatively wide range of stress magnitude individuals successfully adapt to the demands imposed upon them (see Fig. 2). The theory specifies three general modes of adaptive function: dynamic stability (successful adaptation to demands), dynamic instability (vulnerability to failure to effectively adapt to demands), and the transition between these two states (the dotted lines in Fig. 2). Note that the model incorporates both increases (*hyperstress*) and decreases (*hypostress*) in environmental stimulation. Inclusion of the latter accounts for the stress associated with the relative absence of stimulation or environmental demand, although to date direct evidence for such effects in non-sensory, cognitively complex tasks has been lacking.

The theory predicts adaptive stability across a wide range of environmental demand, represented as the plateau in Fig. 2. However, increase or decrease in environmental demand to more extreme levels results in instability in adaptation. As can be seen in Fig. 2, this instability is progressive, such that declines in subjective comfort (e.g., perceived stress and workload; the regions bounded by points A_C and A_Ψ in Fig. 2) begin to occur at levels of stress exposure that are lower than the levels at which performance decrements are observed (the regions bounded by points A_Ψ and A_P in Fig. 2). When the level of stress exceeds the capacity of an adaptive response (i.e., comfort, performance) the resulting range of stress input is a *zone of dynamic instability* in which the form of adaptation becomes unstable and less effective. For *comfort* these are manifested as increased perceived workload and stress, compensatory physiological response (e.g., autonomic arousal, stress hormone release) and compensatory effort (c.f. Hockey, 1997).

Note that in their original conception, Hancock and Warm (1989) regarded hyperstress as an excessive amount of stimulation (too much of something) and hypostress as an insufficient magnitude of environmental stimulation or demand. For instance, they noted that thermal stress occurs at both very high temperatures (hyperstress) and very low temperatures (hypostress). Performance impairment occurs at both extremes (Hancock et al., 2007). In contrast, they identified acoustic noise as exerting its negative effects only in the hyperstress region, as low levels of acoustic noise weakly impacts performance, although recently it has been established that this depends on duration of exposure (Szalma & Hancock, 2011).

Transition from stable to unstable *psychological* adaptation (A_Ψ) results in a zone of dynamic instability that manifests as a performance decrement. The outermost region is failure of physiological adaptation (A_P) which can manifest as unconsciousness (Harris,

Hancock, & Harris, 2005) or the failure of the bodily mechanisms for physical adaptation, as occurs in conditions of prolonged thermal stress above 85 °F effective temperature (Hancock et al., 2007) or when there is sufficient noise intensity to cause sensory damage. The model explicitly defines psychological adaptation in terms of the individual's attentional resource capacity, and physiological adaptation is considered a homeostatic regulation mechanism. The boundaries or transition modes between the zones of adaptability may be continuous, in which case the functions shown in Fig. 2 represent thresholds of adaptive stability. However, Hancock and Warm (1989) argued that the boundaries may instead represent discontinuities or 'catastrophe cusps' in the transition between states of adaptation. This contrasts with the argument by Hockey (1997, 2003) that task-induced stress induces graceful performance degradation rather than precipitous decline.

1.1. The meaning of 'adaptive instability'

It may seem counterintuitive to consider increases in perceived workload and stress as 'instability' of adaptation. Although stress and high workload are often subjectively unpleasant, they include compensatory responses that preserve behavioral and physiological adaptation (c.f., Selye, 1976). Such outcomes do not indicate manifest instability in response and they are not if the sole criterion for effective adaptation is overt performance. However, from the energetic resources perspective the effectiveness of adaptation includes its costs in terms of psychological and physiological energy (e.g., compensatory effort; Hockey, 1997). This cost is based on the assumption that biological systems seek equilibrium states of minimal energy expenditure. An increase in workload or stress therefore represents an adaptive 'instability' even when performance is preserved because the maintenance of the latter increases the energetic costs to the organism, and these costs can render the individual more vulnerable to performance failure as a result of depleted energetic resources. Thus, ranges of task load in which performance is maintained at the cost of compensatory effort (manifested in measures of workload and stress) are considered 'latent performance decrements' (Hockey, 1997).

1.2. Tasks characteristics

A unique feature of the dynamic adaptability theory is that it explicitly identifies the task a person is performing as the dominant
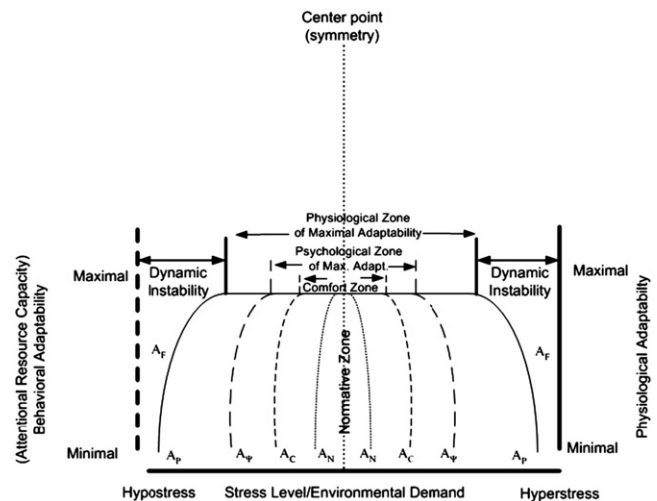
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[1] Note that Hancock and Warm (1989) did not view 'idiographic' as unsystematic, a completely idiosyncratic pattern of response, or the absence of nomothetic mechanisms. They argued that 'output' consists of systematic (i.e., nomothetic) individual differences in response to stress. It does not mean that one cannot predict output, but rather that prediction requires understanding the person factors that influence the response. Perhaps the original theoretical exposition should have used the term 'person factors' or 'individual differences' instead of 'idiographic.' However, the meaning of the latter term has often been misunderstood (Lamiell, 2003).

Center point (symmetry)

Fig. 2. The dynamic adaptability model of Hancock and Warm (1989). *Note.* A_N = adaptive threshold of the normative zone; A_C = adaptive threshold of the comfort zone; A_Ψ = threshold of the psychological zone of adaptability; A_P = threshold of the zone of physiological adaptability; and A_F = zone of adaptive failure at all levels.
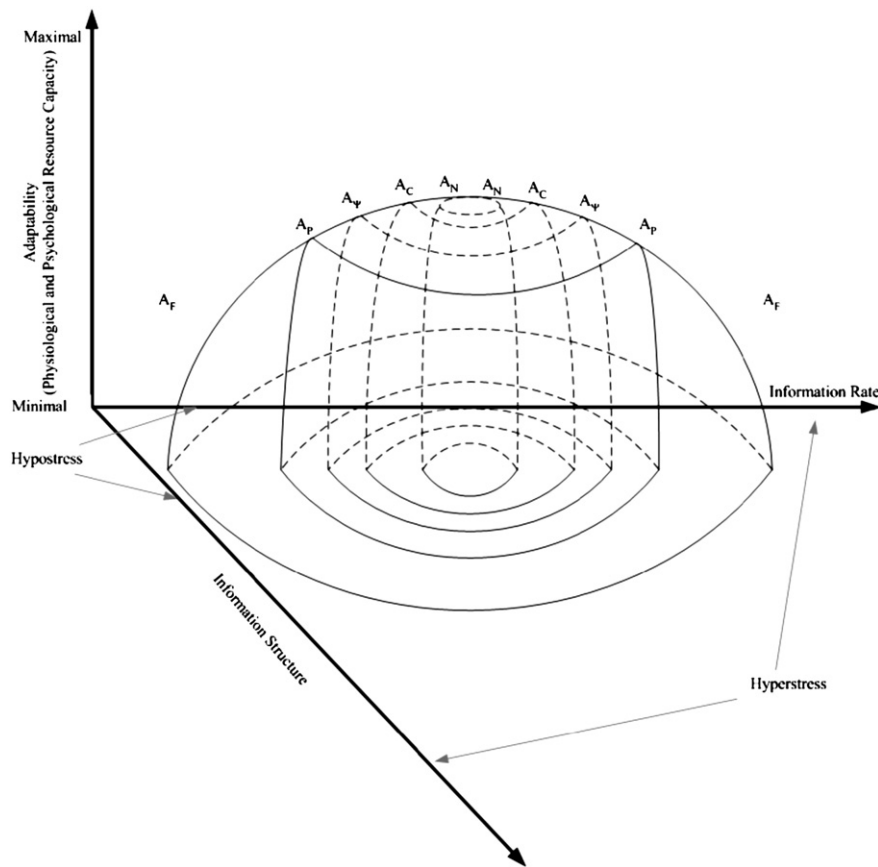
Fig. 3. The dynamic adaptability model of Hancock and Warm (1989), with the stress dimension partitioned into two fundamental dimensions of information from the environment (task): information structure, referring to the spatial representation of the task that conveys its meaning to the individual, and information rate, the temporal characteristics of the task. *Note.* A_N = adaptive threshold of the normative zone; A_C = adaptive threshold of the comfort zone; A_ψ = threshold of the psychological zone of adaptability; AP= threshold of the zone of physiological adaptability; and A_F = zone of adaptive failure at all levels.

source of environmental demand, and it specifies two basic dimensions of information that constitute the task component of the broader demand signature. These dimensions are shown in Fig. 3, which is derived by rotation of Fig. 2 around the ordinate and partitioning the stress axis into its component vectors. *Information structure* refers to the spatial organization of a task (and its resultant meaning for the individual), and *information rate* refers to the temporal properties of a task. Note that each of the two task dimensions is itself composed of multiple components. For instance, the change in performance with time on task manifests as a task duration component of information rate, while the rate of events represents the pacing aspect, and stimulus duration a third component. Hence, better labels for these information components may be 'spatial' and 'temporal' dimensions (c.f., Hancock & Szalma, 2008).

Magnitudes of information structure and rate that are too low or too high induce instability in adaptation. In principle, if these dimensions could be quantified accurately then the collective demands could be represented as a vector that determines the adaptive state of the individual. Such a representation would also permit inclusion of other environmental stimuli (e.g., noise, temperature). Although the vector approach is potentially useful, it is premature to specify a general vector function for performance under stress because of the limited understanding of interactive effects of multiple sources of stress (Hancock & Szalma, 2008) and the difficulty in quantifying information processing (McBride & Schmorrow, 2005). For instance, Hancock and Warm (1989) explicitly represented the two task dimensions as non-orthogonal, but it is not yet clear how this interactivity should be represented within a vector model, or how task dimensions interact with other sources of stress and how these should be represented mathematically. These theoretical refinements

require research in which these inter-relationships can be examined empirically. The present study represents one such effort.

1.3. Performance–workload relationships

One way in which the zones of dynamic instability may manifest in the context of task-induced stress is in the relationship between performance (behavioral response–psychological adaptation, A_ψ) and perceived workload (comfort, A_C). Yeh and Wickens (1988) and Hancock (1996) argued that the pattern of relationships of task manipulations to performance and to perceived workload can reveal the effects of task characteristics on resource supply and demand, and the strategic allocation of resources. Yeh and Wickens (1988) defined cases in which a manipulation impairs performance and increases workload as *associations*, because both measures indicate an increase in resource demand. All other cases are dissociations, because only one measure indicates increased resource demand. However, Hancock differentiated between performance–workload *dissociation*, in which one measure indicated greater consumption of resources (lower performance or higher workload) but the other measured indicated fewer resource demands (improved performance or lower workload). Manipulations in which one measure increased or decreased while the other remained stable are *insensitivities*.[2]

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[2] One could consider insensitivities as *simple dissociations*, and dissociations as *double dissociations*, with the former being a subtype of the latter. However, for the sake of theoretical clarity and empirical consistency with previous research (e.g., Oron-Gilad, Szalma, Stafford, & Hancock, 2008) we retain Hancock's (1996) original terminology.

Hancock (1996; see also Parasuraman & Hancock, 2001) argued that these patterns were diagnostic of different adaptive responses to demands. Hence, performance insensitivity indicates either a compensatory response (when workload increases), such that stability in performance is maintained only at the expense of greater effort; or the development of task-related skills (when workload decreases) that allow the performer to reduce resource allocation to a task while maintaining a stable level of performance. Workload insensitivities reflect either insensitivity of the performer to the quality of his/her behavioral output (when performance declines) or to a floor/ceiling effect with respect to perceived workload. When performance improves workload insensitivity may indicate that the performer has developed task-related skills so that performance requires fewer resources, but the individual has chosen to maintain his/her level of resource investment, thereby improving performance. Note that when task-related skills develop, a strategic decision by the performer determines whether there is performance insensitivity (i.e., the performer chooses to not allocate excess resources to the task) or workload insensitivity (resources are allocated to the task). Dissociations occur either because the person 'gives up' because they do not believe that can achieve task goals (workload and performance both decline), or because the demands are growing but the person is responding successfully so that performance is enhanced at the cost of greater workload (both measures increase).

The patterns of performance–workload relationships can be mapped to the zones of the dynamic instability shown in Fig. 2 (for a more detailed treatment see Oron-Gilad et al., 2008). Region A_N in the Figure represents the normative zone within which an individual is in their normal equilibrium state. Fluctuations of external demands within this region do not require adaptive response and therefore no change in performance or workload is observed; the self-regulation of behavior and information processing is experienced as relatively effortless and automatic. The threshold at point A_N represents the point at which changes in the magnitude of the stressor require compensatory response (at both the physiological and psychological level of analysis) to maintain stable adaptation to changing demands by allocating effort to preserve performance. However, in region A_N–A_C the individual remains within their comfort zone, so engagement of resources in response to increased demand is not appraised as stressful. In this region one would expect that increased task load would increase engagement in the task and energetic arousal (but not tense arousal; Helton, Matthews, & Warm, 2010; Matthews et al., 2002). Regions A_N and A_N–A_C correspond to the *engaged mode* of stress response described by Hockey (1997, 2003), and in region A_N–A_C this can manifest as a dissociation in which performance improves with greater allocation of effort. The individual is engaging in 'effort without distress' (Hockey, 1997, 2003).

At higher magnitudes of demand more resources must be allocated to the task if performance is to be maintained. If the person is operating at or near capacity they may enter region A_C–A_Ψ, in which adaptation in terms of subjective state (comfort) becomes unstable (i.e., perceived workload and stress increase) but the person can maintain performance. This corresponds to what Hockey (1997, 2003) described as *strain mode* ('effort with distress') and manifests as performance insensitivity (workload and stress increase but performance is maintained). Further increase in demand leads to performance failure, as the demands exceed the resource capacity of the person to maintain performance even with increased effort (region A_Ψ–A_P). This can reflect either a strain mode with performance–workload association in which performance declines and workload increases, or to what Hockey (1997, 2003) referred to as a *disengaged mode* in which both performance and workload decrease (a dissociation) due to disengagement from the task ('no effort with no distress'). Note that whichever of the two possible outcomes in region A_N–A_C and A_Ψ–A_P occurs is determined by whether the individual chooses to allocate more effort to task performance (Hockey, 1997).

1.4. Tests of the theory

There have been limited attempts to directly test the predictions of the Dynamic Adaptability Theory regarding changes in performance–workload relationships as a function of variation in information structure and rate. In one early attempt, Hancock and Caird (1993) adapted the theory to test a model of mental workload in which they proposed that workload increases occur when the person's perceived distance from goal achievement increases and/or when the time available for action decreases. If the former is considered a form of information structure and the latter a form of information rate, their model of workload can be viewed as a special application of the more general Dynamic Adaptability Theory. Hancock and Caird (1993) tested their model using a computer-based task in which a grid of circles was presented and participants were to mouse click on a specific sequence of circles that were decreasing in size. Goal distance was manipulated by varying the number of movements required to navigate a sequence of circles (i.e., the number of steps in the sequence), and time for action was manipulated by modulating the rate at which the circles became smaller (shrink rate). They found that increases in task demand impaired performance and increased workload in a manner consistent with their model. However, Hancock and Caird (1993) did not analyze their results in terms of the *relationship* between performance and mental workload to evaluate the more general Dynamic Adaptability Theory, nor did they use a multidimensional appraisal-based measure of perceived stress that includes task engagement as a component.

More recently, Oron-Gilad et al. (2008) reported performance workload relationships in a field study of police officers engaged in firearms training tasks. However, in that study the task dimensions identified in the Dynamic Adaptability Model could not be manipulated, which limited the strength of inferences regarding the pattern of effects. The goal for the present study was to evaluate the Dynamic Adaptability Theory by manipulating the task structure and rate and examining the resultant performance–workload and performance–stress relationships. Based on the model, the form of adaptation (i.e., comfort, performance) and the level of information demand should determine the adaptive state of the individual (i.e., the degree to which the person can effectively maintain comfort, performance, etc.). Stable adaptation is expected at lower levels of demand with precipitous declines in stability at higher levels of task load. Further, as explicitly noted by Hancock and Warm (1989), the two task dimensions will likely interact in influencing response as a function of demand (i.e., the two dimensions will not be orthogonal). The specific hypotheses are summarized below.

1) Higher levels of information demand will be associated with instability in effective adaptation as measured by perceived workload, cognitive state (i.e., stress), and performance.
2) These changes will occur progressively. Based on the nested structure shown in Fig. 2, workload and stress are expected to increase at a level of demand lower than that associated with performance change, although task engagement may also increase if the person engages compensatory resources.
3) The two information dimensions will have interactive effects, such that the magnitude of changes in performance, workload, and stress as a function of information rate will be larger as the demands on the information structure dimension are increased.
4) The relation of outcome measures (adaptive responses) to task demand will be curvilinear, with a precipitous change at the thresholds of adaptation. An alternative hypothesis, based on Hockey (1997; 2003) is that graceful degradation will be observed (i.e., a shallower slope for the degradation function).

These hypotheses were tested by manipulating the two dimensions specified by the Dynamic Adaptability Theory, and evaluating their effects on the different forms of adaptation defined in terms of

outcome measures. Information structure was manipulated by varying source complexity (i.e., the number of displays to be monitored; Davies & Parasuraman, 1982), and information rate was manipulated by varying the rate of stimulus presentation. Subjective comfort was measured in terms of perceived workload and stress, and psychological adaptation was measured in terms of performance, per Hancock and Warm's (1989) original interpretation. A short duration (12 min) signal detection task was employed, in which critical signals were pairs of digits that differed by 0 or 1.

2. Method

2.1. Participants

Three hundred and eighteen psychology undergraduates (126 males, 192 females) at a large southeastern U.S. university were recruited for the study, and received course credit in exchange for participation. Participant ages ranged from 17 to 32 years ($M = 18.4$, $SD = 1.5$).

2.2. Task

The task consisted of an adaptation of the cognitive vigilance task employed by Warm, Howe, Fishbein, Dember, and Sprague (1984), in which participants monitored the visual presentation of 2-digit numbers ranging from 01 to 99. The displays were created using Microsoft PowerPoint in 28 point Arial font. Participants were instructed to respond by pressing the spacebar on a computer keyboard when a critical signal appeared on the screen. Critical signals were defined as instances in which the two digits differed by 0 or 1 (e.g. 01, 54, 99), and all other digit pairs were defined as neutral events requiring no overt response from the observer.

Throughout the task, two 2×2 grids appeared side-by-side on the screen and each of the 8 cells was a "display" in which the digits appeared (see Fig. 4). The two grids were separated in order to simplify the manipulation of the 2- and 4-display conditions, and also to maintain the 2×2 grid format used in previous research on source complexity in vigilance and signal detection (e.g., Grubb, Warm, Dember, & Berch, 1995). For the 1, 2 and 4 display conditions, the locations of the monitored displays were selected at random for each participant, with the restriction that the displays to be monitored were always within the same 2x2 grid. Before each condition, there was a 'notification screen', on which a red outline surrounding the display(s) notified participants of the number and location(s) of the display(s) to be monitored for that condition. The red outline was not present during the tasks.

Across all experimental conditions stimulus duration was 2500 ms, determined via a pilot study which indicated that this was the minimum duration required to scan all 8 displays. The number of critical signals was set at 10 per 3-minute block of trials across all conditions. The number of neutral events differed for the different levels of event rate. For each condition there were four continuous 3-minute blocks, a practice block and three test blocks. The task duration was thus 12 min for each condition, but only the three test blocks (9 min) were used in the analyses of results.

| 64 | 02 | | 64 | 60 |
| 53 | 70 | | 39 | 74 |

Fig. 4. Example of the displays used in the present study.

Note that although holding the number of targets constant provides an equivalent number of critical signal exposures, it does confound event rate with signal probability. One can hold signal probability constant, but this would then confound event rate with the number of critical signals presented. Following the vigilance literature, we held the number of targets constant and permitted signal rate and event rate to covary as this is common practice in vigilance research (e.g., Lanzetta, Dember, Warm, & Berch, 1987; Jerison & Pickett, 1964; Loeb & Binford, 1968; Parasuraman, 1979; Taub & Osborne, 1968). Although studies of visual search have consistently found that performance is negatively related to target prevalence (Wolfe, Horowitz, & Kenner, 2005; Wolfe et al., 2007), Warm and Jerison (1984) noted that the evidence indicates that "the effects of event rate transcend factors in the simple probability of signals" (page 23) because detection probability is negatively related to event rate even when signal probability is equated.

2.3. Experimental design

The experiment consisted of a 4 (information rate) by 4 (information structure) factorial design with repeated measures on the second factor. Information rate was manipulated by varying the rate of stimulus presentation (event rate). The four event rates were 8 ($n = 80$), 12 ($n = 79$), 16 ($n = 80$), and 20 ($n = 79$) events/min. Each participant was assigned at random to one of these four levels. Information structure was manipulated by varying the source complexity (i.e., the number of the displays to be monitored: 1, 2, 4 or 8; 0, 1, 2, or 3 bits of uncertainty, respectively; Davies & Parasuraman, 1982; c.f., Grubb et al., 1995). Note that source complexity is analogous to set size in visual search paradigms, and it has been well established that performance declines as a function of increasing set size (e.g., Benjamins, Hooge, van Elst, Wertheim, & Verstraten, 2009; Cameron, Tai, Eckstein, & Carrasco, 2004; Pavlovskaya, Ring, Groswasser, Keren, & Hochstein, 2001; Treisman & Gelade, 1980; Wolfe, 1994). The order in which these four levels were presented was balanced across participants via a Latin Square.

2.4. Measures

2.4.1. Perceived workload

The NASA-Task Load Index (TLX; Hart & Staveland, 1988) served as the measure of perceived workload. The TLX provides an index of global workload as well as ratings on six subscales, three of which reflect appraisals of the task (Mental Demand, Physical Demand, Temporal Demand) and three of which reflect appraisals of the participant's own response to the task (Perceived Performance, Effort, and Frustration). The rating scales range from 0 to 100. Each 'subscale' is a single item, and global workload is computed as an average of the six scales.

2.4.2. Stress

Perceived stress was measured using the short twenty-item version of the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999, 2002) which consists of three scales that reflect the cognitive, affective, and motivational dimensions of stress. Task engagement reflects the cognitive (concentration) and energetic/motivational (energetic arousal, motivation) components of cognitive state; distress reflects both cognitive (perceived confidence and control) and affective (hedonic tone and tense arousal) aspects of stress; and worry reflects the cognitive dimension of stress (task-related and task-unrelated thoughts, self-focused attention, and self-esteem). Matthews et al. (2002) have identified the core relational theme (Lazarus, 1999) associated with each scale. Task engagement is linked to the theme of commitment of effort, distress is associated with the theme of overload of processing capacity, and worry reflects the theme of self-evaluation. Participants rated the DSSQ items (7 task engagement items, 7 distress

items, and 6 worry items) on a 5-point rating scale. Scores vary from 0 to 35 for task engagement and distress and 0 to 30 for worry.

2.5. Procedure

Data were collected in groups of up to nine participants in a laboratory equipped with nine computer work stations separated by cubicle walls to prevent visual contact between participants. In addition, participants wore noise canceling headphones during the experiment to prevent distraction from ambient sound. At no time during the session did any of the participants communicate with one another. Participants surrendered their cell phones, pagers, and wristwatches prior to performing the task. Participants completed the pre-task version of the stress state questionnaire (DSSQ) immediately prior to the first task condition. Each condition was 12 min in duration, with the first 3 min serving as practice trials to familiarize the participants with the task. After each display condition participants completed the TLX and DSSQ, the order of which was counterbalanced across participants. The duration of the entire study was approximately 2 h.

3. Results

Performance and workload were each analyzed via a 4 (event rate) × 4 (source complexity) mixed analysis of variance (ANOVA) with repeated measures on the second factor. Each of the three DSSQ scales were analyzed via an ANCOVA with the corresponding pre-task state entered as a covariate. Due to technical problems some participants did not complete several items on the subjective measures and so were not included in the analyses for those variables. Hence, the degrees of freedom are not constant across analyses. Violations of sphericity were corrected using the Greenhouse–Geisser adjustment of degrees of freedom (Maxwell & Delaney, 2004). As the independent variables in this study were quantitative, statistically significant effects involving event rate were further analyzed by trend analyses using hierarchical regression (e.g., Pedhazur, 1997), and for significant main effects of display the trends were evaluated using within-subjects polynomial contrasts. To facilitate comparison of patterns of performance, workload, and stress, all analyses were computed using z-scores of each dependent variable (computed for each dependent measure using the respective mean and standard deviation for the entire sample) and, when appropriate (i.e., regression analyses of trends) on the independent variable (event rate). The means and standard deviations of the untransformed scores are summarized in Tables 1a, 1b, and 1c for each dependent measure. The figures displaying the trend analyses consist of the z-scores.

3.1. Performance

3.1.1. Proportion of signals detected

The proportion of correct detections is plotted as a function of event rate for the four source complexity conditions in Fig. 5a. ANOVA revealed significant main effects for source complexity, $F(3,842) = 921.60$, $p<.001$, $\omega^2 = .69$, and for event rate, $F(3,314) = 23.39$, $p<.001$, $\omega^2 = .05$. As expected, in each case higher levels of demand were associated with fewer correct detections. The source complexity by event rate interaction was also statistically significant, $F(8,842) = 11.68$, $p<.001$, $\omega^2 = .07$. Trend analyses of accuracy as a function of event rate within each source complexity condition indicated a linear (Lin) decline in the 1-display condition, $F(1,317) = 6.66$, $p=.01$, $R^2 = .02$, $\beta_{Lin} = -.143$, $t(317) = 2.58$, $p=.01$, and curvilinear relationships in the other three conditions. Linear and quadratic (Quad) trends were observed for the 2-display condition, $F(2,316) = 13.09$, $p<.001$, $R^2 = .07$, $\beta_{Lin} = -.252$, $t(316) = 4.66$, $p<.001$, $\beta_{Quad} = -.116$, $t(316) = 2.14$, $p=.03$. A cubic relationship was observed for the 4-display condition, $F(3,315) = 25.63$, $p<.001$, $R^2 = .20$, $\beta_{Cubic} = -.435$, $t(315) = 2.41$, $p<.001$. Statistically significant quadratic and cubic terms were

Table 1a
Means and standard deviations for performance measures.

Event rate (per min)	Displays				n
	1	2	4	8	
Proportion of correct detections					
8	0.95 (0.14)	0.89 (0.18)	0.87 (0.16)	0.55 (0.16)	80
12	0.93 (0.19)	0.88 (0.17)	0.75 (0.18)	0.51 (0.15)	79
16	0.90 (0.21)	0.86 (0.17)	0.74 (0.16)	0.49 (0.14)	80
20	0.88 (0.21)	0.76 (0.21)	0.63 (0.18)	0.28 (0.12)	80
Proportion of false alarms					
8	0.01 (0.03)	0.03 (0.06)	0.02 (0.03)	0.10 (0.09)	80
12	0.01 (0.03)	0.01 (0.03)	0.02 (0.04)	0.05 (0.04)	79
16	0.02 (0.06)	0.02 (0.05)	0.03 (0.07)	0.06 (0.11)	80
20	0.01 (0.04)	0.02 (0.07)	0.03 (0.10)	0.06 (0.15)	80
RT correct detections					
8	1.14 (0.49)	1.34 (0.34)	1.71 (0.39)	2.05 (0.56)	80
12	0.97 (0.26)	1.27 (0.30)	1.63 (0.31)	1.93 (0.31)	79
16	0.98 (0.34)	1.22 (0.26)	1.46 (0.25)	1.72 (0.33)	80
20	0.95 (0.23)	1.28 (0.26)	1.46 (0.25)	1.62 (0.46)	80
RT false alarms					
8	0.74 (1.64)	0.94 (1.33)	1.33 (1.82)	2.34 (0.70)	80
12	0.51 (1.05)	0.79 (1.03)	1.15 (1.16)	1.90 (0.70)	79
16	0.35 (0.68)	0.64 (0.79)	1.08 (1.05)	1.96 (0.60)	80
20	0.54 (0.77)	0.68 (0.89)	1.03 (0.90)	1.52 (0.58)	80

Note. Standard deviations are in parentheses.

Table 1b
Means and standard deviations for perceived workload.

Event rate (per min)	Displays				n
	1	2	4	8	
Global workload					
8	23.42 (17.64)	30.07 (18.39)	34.44 (15.60)	52.62 (17.06)	80
12	24.62 (17.87)	29.21 (15.96)	36.78 (22.64)	50.53 (17.61)	79
16	26.97 (17.77)	30.87 (18.18)	38.89 (15.82)	52.49 (16.26)	80
20	30.10 (18.57)	37.47 (17.27)	44.27 (15.37)	56.29 (14.34)	80
Mental demand					
8	28.03 (26.27)	39.74 (27.19)	48.38 (26.44)	67.21 (28.41)	80
12	31.37 (28.14)	37.03 (27.63)	48.10 (28.74)	63.72 (29.62)	79
16	34.55 (28.90)	39.01 (27.59)	53.51 (27.16)	72.19 (24.27)	80
20	36.96 (28.04)	48.40 (27.46)	57.40 (24.85)	71.45 (24.55)	80
Physical demand					
8	8.42 (14.75)	12.56 (18.67)	12.92 (17.78)	19.16 (24.99)	80
12	10.38 (16.71)	14.39 (19.20)	14.09 (17.46)	21.37 (23.62)	79
16	12.22 (15.29)	12.21 (16.71)	17.34 (20.03)	15.41 (21.82)	80
20	13.73 (17.17)	15.35 (18.12)	15.76 (18.98)	18.89 (20.31)	80
Temporal demand					
8	23.75 (25.05)	36.09 (28.87)	44.09 (26.28)	71.43 (25.75)	80
12	23.68 (26.82)	29.80 (28.23)	40.57 (29.23)	64.49 (30.87)	79
16	30.51 (30.30)	34.68 (29.47)	46.69 (26.68)	69.59 (29.58)	80
20	31.89 (27.96)	43.38 (28.57)	51.55 (28.45)	72.11 (26.05)	80
Perceived performance					
8	24.28 (29.78)	26.41 (29.02)	24.05 (21.31)	41.17 (26.92)	80
12	26.20 (32.35)	28.53 (30.73)	30.82 (26.63)	43.16 (26.80)	79
16	26.39 (30.24)	25.45 (26.74)	30.00 (23.33)	45.07 (26.15)	80
20	30.85 (31.62)	28.93 (24.79)	36.28 (23.04)	50.51 (23.96)	80
Effort					
8	33.22 (31.21)	39.74 (29.63)	50.78 (29.05)	66.51 (27.13)	80
12	35.32 (28.60)	41.60 (27.38)	57.66 (87.51)	60.82 (27.52)	79
16	36.96 (31.51)	47.92 (30.40)	55.06 (28.02)	65.68 (26.87)	80
20	39.35 (30.69)	52.79 (28.04)	57.43 (28.64)	65.59 (27.18)	80
Frustration					
8	22.83 (30.80)	25.90 (31.01)	26.43 (29.37)	49.67 (31.92)	80
12	20.81 (29.92)	24.13 (28.82)	29.43 (31.09)	44.94 (34.72)	79
16	21.22 (27.52)	24.08 (26.70)	33.47 (29.40)	47.74 (31.19)	80
20	27.80 (28.80)	36.29 (31.49)	47.70 (32.44)	59.21 (30.81)	80

Note. Standard deviations are in parentheses.

Table 1c
Means and standard deviations for stress measures.

Event rate (per min)	Pre-task	Displays				n
		1	2	4	8	
Task engagement						
8	13.40 (3.93)	9.26 (5.15)	10.27 (4.91)	10.81 (4.61)	11.03 (4.56)	78
12	12.85 (3.88)	10.82 (4.13)	9.87 (4.71)	9.95 (5.07)	10.41 (4.81)	79
16	12.42 (4.54)	10.08 (4.28)	10.58 (4.74)	10.23 (4.32)	11.03 (3.69)	79
20	13.47 (3.56)	10.47 (4.30)	10.19 (4.68)	10.00 (5.03)	10.39 (4.86)	74
Distress						
8	5.99 (3.44)	4.54 (3.59)	5.31 (3.81)	5.81 (3.83)	7.86 (4.28)	78
12	5.94 (3.51)	4.90 (3.58)	5.21 (3.66)	6.91 (3.79)	8.49 (3.99)	79
16	6.15 (3.33)	4.73 (3.75)	5.75 (3.87)	6.66 (3.42)	9.29 (3.40)	77
20	6.30 (3.63)	5.69 (3.98)	6.12 (3.50)	8.22 (3.71)	9.04 (3.66)	74
Worry						
8	11.74 (4.91)	10.33 (6.81)	9.90 (6.62)	9.22 (6.18)	8.23 (6.68)	78
12	11.19 (5.74)	8.78 (5.85)	8.39 (6.61)	8.63 (6.28)	8.20 (6.26)	79
16	11.43 (4.53)	10.57 (5.95)	10.64 (5.75)	9.83 (6.39)	7.85 (5.78)	79
20	10.68 (5.21)	9.76 (6.05)	9.68 (6.13)	9.00 (6.19)	8.99 (6.33)	74

Note. Standard deviations are in parentheses.

observed for the 8-display condition, $F(3,314) = 59.08$, $p<.001$, $R^2 = .36$, $\beta_{Quad} = -.240$, $t(314) = 5.32$, $p<.001$, $\beta_{Cubic} = -.539$, $t(314) = 3.35$, $p = .001$. For each of the curvilinear relationships, the level of performance accuracy was relatively stable at lower event rates and declined at the higher event rates.

3.1.2. Proportion of false alarms

The proportion of false alarms is plotted as a function of event rate for the four source complexity conditions in Fig. 5b. ANOVA indicated a significant main effect for source complexity, $F(3,551)$, $p<.001$, $\omega^2 = .19$, but not for event rate ($p = .26$). However, a statistically significant event rate by source complexity interaction was observed, $F(5, 551) = 5.91$, $p<.001$, $\omega^2 = .03$. Trend analyses for event rate within each display condition revealed that the only statistically significant effects were for the linear and quadratic trends in the 8-display condition, $F(2,315) = 4.80$, $p = .009$, $R^2 = .03$, $\beta_{Lin} = -.121$, $t(315) = 2.18$, $p = .03$, $\beta_{Quad} = .121$, $t(315) = 2.18$, $p = .03$. The pattern of results indicates that there was little change in false alarms as a function of event rate when the level of display uncertainty was low, but at the highest level of structural demand false alarms declined as event rate increased to the mid-range (minimum at ~16 events/min), after which false alarms increased.

3.1.3. Response time on correct detection trials

Median response time on correct detection trials is plotted as a function of event rate and source complexity condition in Fig. 6. Statistically significant effects were observed for source complexity, $F(2,723) = 650.82$, $p<.001$, $\omega^2 = .61$, event rate, $F(3,307) = 22.37$, $p<.001$, $\omega^2 = .05$, and the interaction between these two factors, $F(7,723) = 7.17$, $p<.001$ $\omega^2 = .21$. Trend analyses for response time as a function of event rate within each display condition revealed a linear relationship for the 1-, $F(1,314) = 10.93$, $p = .001$, $R^2 = .03$, $\beta_{Lin} = -.183$, $t(314) = 3.31$, $p = .001$, 2-, $F(1,314) = 7.03$, $p = .008$, $R^2 = .02$, $\beta_{Lin} = -.087$, $t(314) = 2.65$, $p = .008$, 4-, $F(1,316) = 45.93$, $p<.001$, $R^2 = .13$, $\beta_{Lin} = -.244$, $t(316) = 6.77$, $p<.001$, and 8-display conditions, $F(1,313) = 65.53$, $p<.001$, $R^2 = .17$, $\beta_{Lin} = -.380$, $t(313) = 8.10$, $p<.001$. In each case higher event rate predicted faster response times and the linear change was generally larger as a function of increasing display uncertainty.

3.1.4. Response time on false alarm trials

Median response time on false alarm trials is plotted as a function of event rate and source complexity condition in Figs. 7a and 7b, respectively. Statistically significant effects were observed for source complexity, $F(2, 88) = 2.77$, $p = .044$, $\omega^2 = .01$, and event rate, $F(3,315) = 7.11$, $p = .001$, $\omega^2 = .03$. The interaction between
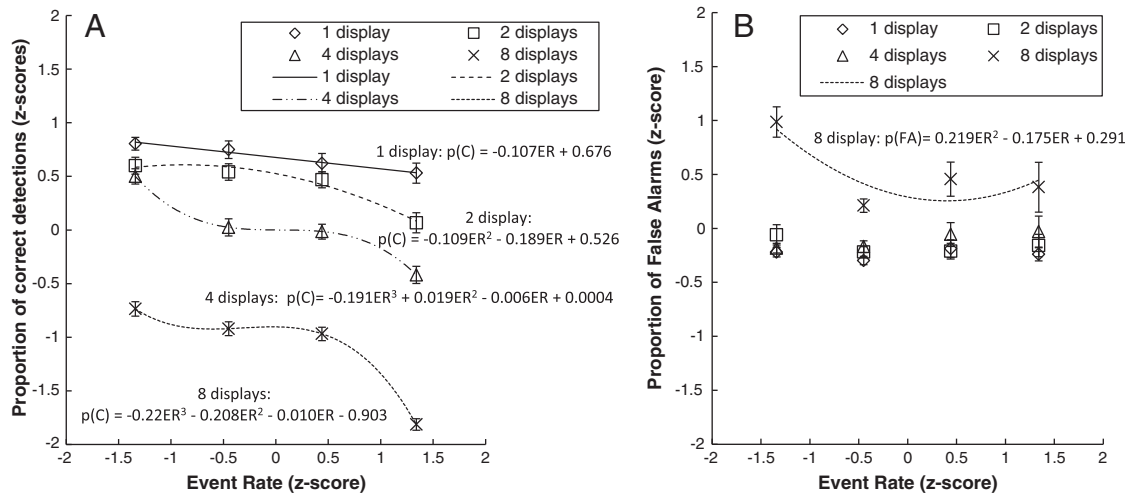

Fig. 5. Z-scores for the proportion of signals detected (A) and the proportion of false alarms (B) as a function of display uncertainty and event rate. In each case the functions were fitted to the data points. *Note.* Error bars are standard errors.
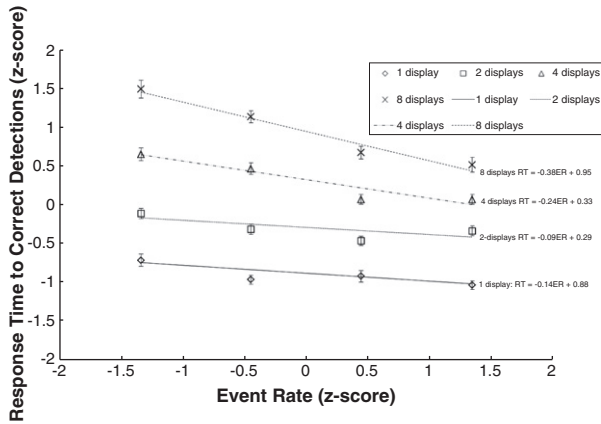
Fig. 6. Z-scores for median response time for correct detections as a function of display uncertainty and event rate. In each case the functions were fitted to the data points. *Note.* Error bars are standard errors.

these factors was not statistically significant ($p = .090$). Trend analysis for event rate indicated significant linear and quadratic terms, $F(1,314) = 58.71$, $p < .001$, $R^2 = .27$, $\beta_{Lin} = -.508$, $t(314) = 10.48$, $p < .001$, $\beta_{Quad} = .116$, $t(314) = 2.41$, $p = .016$. For source complexity the within-subjects polynomial contrasts indicated a marginally significant linear trend, $F(1,40) = 3.63$, $p = .064$, $\omega^2 = .01$ (see Fig. 7B). Response time increased as a function of source complexity but decreased as a function of event rate.

3.1.5. Speed–accuracy tradeoff: analysis of information throughput

To further explore the pattern of speed–accuracy relationships as a function of information rate and information structure, the rate of accurate information processing (throughput; Thorne, 2006) was computed by dividing the number of correct detections by the cumulative response time (both correct and incorrect responses). As Thorne (2006) noted, this measure may be conceptualized as the number of accurate decisions per unit of time available to make a decision. In the case of a two-choice task, as in the present study, this measure corresponds to bits of information processed per unit time.

ANOVA indicated statistically significant effects for source complexity, $F(2,627) = 942.81$, $p < .001$, $\omega^2 = .69$, and event rate, $F(3,314) = 3.80$, $p = .011$, $\omega^2 = .01$. The interaction between these factors was not statistically significant ($p = .48$). For event rate linear and quadratic

trends were observed, $F(2,316) = 5.73$, $p = .004$, $R^2 = .04$, $\beta_{Lin} = -.138$, $t(316) = 2.49$, $p = .013$, $\beta_{Quad} = -.126$, $t(316) = 2.28$, $p = .023$, reaching a maximum at ~16 events/min (see Fig. 8a). Increasing event rate up to that level increased throughput, with a decline in performance thereafter. That is, as the rate of information presentation is increased, channel capacity increased (i.e., the rate of information transfer without error increased) up to a maximum point. For source complexity within-subjects polynomial contrasts indicated significant linear, quadratic, and cubic terms for display, as shown in Fig. 8b. As information uncertainty increased throughput (channel capacity) decreased, with relative stability in the 4-display range.

3.2. Workload

3.2.1. Global workload

Mean global workload scores are plotted as a function of event rate and display condition in Fig. 9a and b, respectively. Technical problems with computer data collection resulted in a number of missing values for the weights of the six components of the TLX. Analyses were therefore computed using the unweighted average and unweighted ratings. A significant main effect on global workload was obtained for source complexity, $F(2,633) = 227.28$, $p < .001$, $\omega^2 = .35$, and event rate, $F(3,274) = 2.99$, $p = .031$ $\omega^2 = .005$. The interaction between these factors was not statistically significant ($p = .63$). For source complexity the within subjects polynomial contrasts indicated statistically significant linear, $F(1,274) = 380.25$, $p < .001$, $\omega^2 = .78$, and quadratic trends, $F(1,274) = 56.83$, $p < .001$, $\omega^2 = .35$. For event rate a significant linear trend was observed, $F(1,310) = 11.43$, $p = .001$, $R^2 = .03$, $\beta_{Lin} = .189$, $t(310) = 3.38$, $p = .001$.

3.2.2. Subscales

Analyses of the six components (i.e. Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, Frustration) of perceived workload indicated a significant main effect of source complexity for each scale (Mental Demand: $F(2,658) = 186.98$, $p < .001$, $\omega^2 = .31$, Physical Demand: $F(2,741) = 17.37$, $p < .001$, $\omega^2 = .04$, Temporal Demand: $F(2,704) = 195.62$, $p < .001$, $\omega^2 = .32$, Performance: $F(2,772) = 48.51$, $p < .001$, $\omega^2 = .10$, Effort: $F(2,580) = 46.04$, $p < .001$, $\omega^2 = .10$, and Frustration: $F(2,753) = 85.58$, $p < .001$, $\omega^2 = .17$). The only statistically significant effects for event rate were associated with Temporal Demand, $F(3,284) = 3.00$, $p = .031$, $\omega^2 = .005$, and Frustration, $F(3,281) = 4.70$, $p = .003$, $\omega^2 = .009$. For each independent variable, when effects were observed they generally conformed to that of global
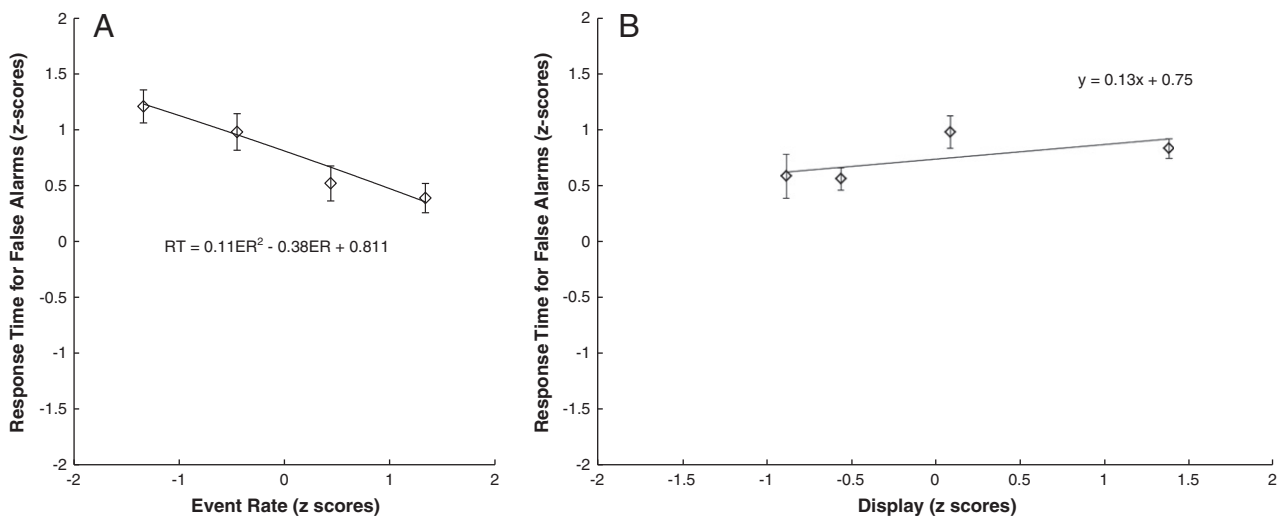

Fig. 7. Z-scores for median response time for false alarms as a function of event rate (A) and source complexity (B). In each case the functions were fitted to the data points. *Note.* Error bars are standard errors.
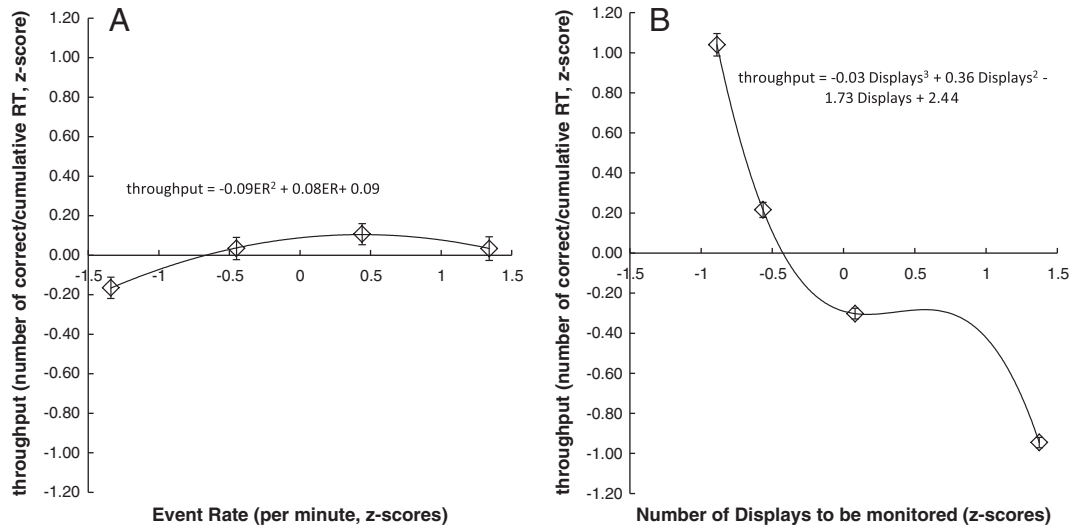
Fig. 8. Throughput (bits/min) as a function of event rate (A) and source complexity (B). In each case the functions were fitted to the data points. *Note*. Error bars are standard errors.

workload: Perceived workload increased as a function of task demand. A statistically significant source complexity by event rate interaction was observed for Physical Demand, $F(7,741) = 2.04$, $p = .041$, $\omega^2 = .007$. Trend analyses for the Physical Demand scale as a function of event rate indicated a significant linear trend in the 1-display condition, $F(1,306) = 4.68$, $p = .031$, $R^2 = .02$, $\beta_{Lin} = .129$, $t(300) = 2.27$, $p = .024$. There were no significant trends for the other display conditions ($p > .11$ in each case). The display by event rate interaction was not statistically significant for the other five scales ($p > .17$ in each case).

3.3. Stress

ANOVAs indicated that there were no statistically significant differences in pre-task engagement, distress, or worry as a function of event rate ($p > .31$ in each case). To evaluate the effects of information rate and structure on post-task stress an ANCOVA was computed for each of the three scales, with the corresponding pre-task state entered as the covariate. Significant source complexity effects were observed for perceived task engagement, $F(2,811) = 2.81$, $p = .04$, $\omega^2 = .004$ (Fig. 10a), distress, $F(2,682) = 101.02$, $p < .001$, $\omega^2 = .19$

(Fig. 10b), and worry, $F(2,835) = 10.06$, $p < .001$, $\omega^2 = .02$ (Fig. 10c). Post-task distress increased and worry decreased as a function of the number of displays to be monitored. A significant source complexity by event rate interaction was observed for perceived task engagement, $F(8,811) = 2.27$, $p = .02$, $\omega^2 = .009$. Hierarchical trend analyses of perceived task engagement as a function of event rate within each source complexity condition were computed, with the pre-task state entered first. There was a statistically significant quadratic term for the 1-display condition, $F(3,304) = 23.80$, $p < .001$, $R^2 = .19$, $\beta_{pre} = .427$, $t(304) = 8.24$, $p < .001$, $\beta_{Quad} = -.106$, $t(304) = 2.04$, $p = .042$ (see Fig. 10a). There were no statistically significant trends as function of event rate for the other display conditions ($p > .16$ in each case). Hence, the source complexity by event rate interaction derived from the change in self-reported task engagement as a function of increasing event rate in the 1-display condition, reaching a level of relative stability at ~15 events/min. There were no significant interaction effects for the distress and worry scales ($p > .13$ in each case). In sum, the subjective stress induced by higher levels of information structure demand was restricted to the affective component of stress. The motivational (task engagement) and cognitive (worry, e.g., task unrelated thoughts)
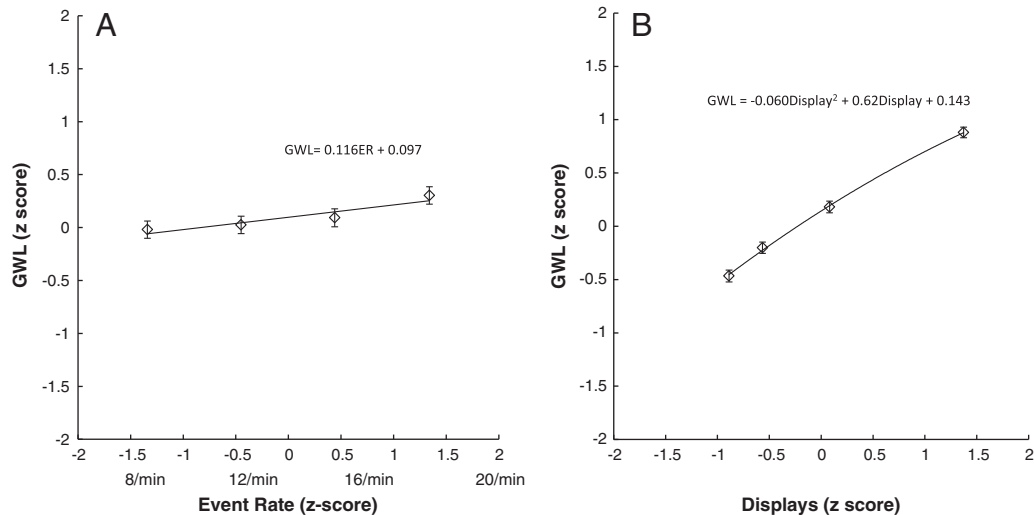

Fig. 9. Global workload (z-scores) as a function of event rate (A) and source complexity (B). In each case the functions were fitted to the data points. *Note*. Error bars are standard errors.
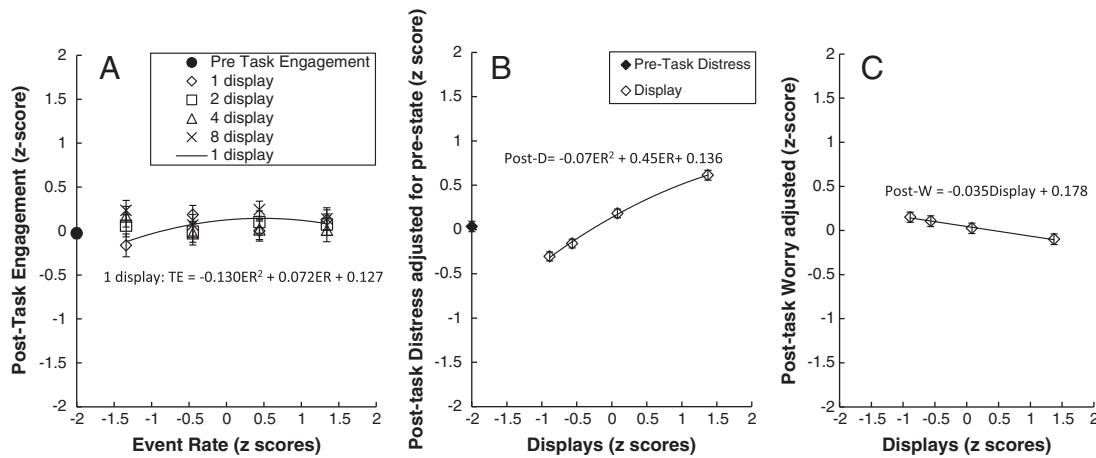
Fig. 10. Post-task stress (z-scores of means adjusted for pre-task state) as a function of event rate for post-task engagement (A), and display uncertainty for post-task distress (B), and post-task worry (C). In each case the functions were fitted to the data points. *Note.* Error bars are standard errors.

dimensions showed a decline in stress as a function of the number of displays to be monitored. There were no significant main effects of event rate for the three scales ($p > .09$ in each case).

3.3.1. Interactions of independent variables with pre-task states

There were no statistically significant interactions involving pre-task state for distress or task engagement ($p > .07$ in each case). A significant source complexity by event rate by pre-task state interaction was observed for worry, $F(8,835) = 2.65$, $p = .005$, $\omega^2 = .02$, indicating that the relationship of pre-task to post-task worry was moderated by task characteristics. However, separate event rate by pre-task worry ANCOVAs within each display condition indicated that there were no statistically significant effects for event rate or for the interaction of event rate and pre-task worry ($p > .06$ in each case). Correlational analyses within each event rate condition revealed statistically significant correlations between pre- and post-task worry, and these relationships were generally greater in magnitude as event rate increased (see Table 2). Thus, higher levels of pre-task worry rendered participants more vulnerable to the cognitive stress effects of information demand, such that the relationship between pre-post task worry was larger in magnitude at the three higher event rates relative to the lowest level of temporal demand.

4. Discussion

The purpose for this study was to test elements of the Dynamic Adaptability Theory of stress and performance proposed by Hancock and Warm (1989). Specifically, the effects of variation in information structure and rate on adaptive response in terms of performance, perceived workload, and stress were investigated. Consistent with hypothesis 1 and research on the inverse relationship between target prevalence and performance accuracy (Wolfe et al., 2005, 2007), performance accuracy generally declined as event rate increased, but for the three conditions consisting of multiple displays the decline varied

Table 2
Correlations between pre- and post-task worry.

Event rate	Display				N
	1	2	4	8	
8	.12	.32*	.25	.38*	77
12	.54*	.42*	.56*	.69*	79
16	.42*	.38*	.48*	.21	73
20	.46*	.59*	.46*	.44*	73

* $p < .05$ after Bonferroni correction ($\alpha = .0125$).

in form and occurred only in specific ranges of temporal demand (i.e., the relationship was curvilinear).

In contrast, linear relationships were observed between response time to correct detections and event rate. Higher levels of structural demand were associated with steeper slopes for these functions, but response time was *faster* as a function of event rate and *slower* as a function of source complexity. Further, the form of the relationship of each dimension to performance varied as a function of the other dimension and of the performance measure itself (accuracy vs. response time). However, perceived workload and stress functions for each dimension were similar across levels of the other dimension (i.e., there were no interactive effects). Thus, the functions describing adaptive instability may not have a parallel, nested structure of different thresholds of precipitous change in adaptation for subjective state and task performance. Further, these functions do not exhibit symmetry across task dimensions, as indicated in the model shown in Fig. 2. In other words, hypothesis 2 was not supported.

One could make the post-hoc argument that the magnitudes of demands in this study were restricted to those ranges of information rate and information structure in which both forms of adaptation exhibited instability (i.e., region A_Ψ–A_P in Fig. 2). This is unlikely, however. The least demanding condition (1 display at 8 events/min) was associated with high performance accuracy (correct detections $M = 95\%$; false alarms $M = 1\%$) and with low workload ($M = 23.42$), and distress ($M = 4.54$), suggesting this condition lay within the comfort zone shown in Fig. 2 (specifically, region A_N–A_C). In contrast, the most demanding condition (8 displays at 20 events per minute) was associated with very poor performance accuracy (correct detections $M = 28\%$; false alarms $M = 6\%$), higher workload ($M = 56.29$), and greater distress ($M = 9.04$). In addition, the reduction in accuracy and response time associated with the event rate manipulation is consistent with prior research on the effect of target prevalence on visual search performance.

Hence, the current results are not likely an artifact of range effects. Instead, it appears that the progressive changes in adaptation in which subjective comfort declines at lower levels of demand than performance (see Fig. 2) may not be ubiquitously true. The evidence from this study does not preclude the possibility that there may be tasks in which such progressive functions occur, but it does indicate that relative positions of the nested functions may depend on the nature of the task itself (i.e., which components of information structure and rate are dominant for a given task). Future research should vary the specific nature of the task (e.g., different kinds of information processing tasks, and different manipulations of information rate and structure) to assess the generality of these results.

Hypothesis 3, that the information dimensions would not be orthogonal, was confirmed for performance measures, but task variables generally exerted independent effects upon workload and stress. The latter results were consistent with those of Hancock and Caird (1993), who reported no significant interaction of spatial and temporal dimensions of task demand for either the TLX or the SWAT, an alternative measure of perceived workload (Reid & Nygren, 1988). Recall that Hancock and Warm (1989) proposed that the set of environmental demands (which they referred to as a 'stress signature') could in principle be represented as multivariate vector in which the two task dimensions are combined with other environmental stimuli (e.g., noise, temperature) that affect adaptation. It may be that the way in which these variables combine itself varies according to the form of adaptive response measured (i.e., performance vs. subjective state). If this proves to be the case, then future refinement of the theory should specify conditions under which the dimensions of stress combine additively or multiplicatively.

The prediction for hypothesis 4 was that the relation of outcome measures (adaptive responses) to task demand would be curvilinear, with a precipitous change at thresholds of adaptation. This prediction was confirmed only at the most extreme condition (i.e., 8-display) and only for accuracy. At lower levels of information structure event rate functions were linear (1-display), curvilinear with a decline in accuracy at the extremes of demand (4-display), or curvilinear with a gradual decline at the highest level of demand (2-display; see Fig. 5a). In addition, the loss of comfort (the transition at point A_C in Fig. 2) was not precipitous as predicted by the Dynamic Adaptability Theory but was more consistent with the gradual ('graceful') degradation predicted by Hockey (1997).[3] However, both perspectives propose that individuals can effectively adapt to increases in demand by allocating more resources to the task. Results indicate that for performance the strategy of resource allocation varied as a function of the nature of the demand (i.e., structural vs. temporal), which manifested in the relationships between speed and accuracy across experimental conditions.

4.1. Speed/accuracy tradeoffs

The relationship between speed and accuracy as a function of event rate varied in form across levels of source complexity. Across all display conditions response time to correct detections declined as a linear function of event rate. In the 1-display condition accuracy also declined linearly as a function of event rate, indicating a strategy of speed over accuracy to compensate for the increased temporal demand. This result is similar to those reported previously in the contexts of visual search tasks (Wolfe et al., 2005). For the 2-display condition accuracy remained relatively stable until the highest event rate, at which point performance declined, revealing a speed accuracy tradeoff only at the highest levels of temporal demand (i.e., the difference between the 16 and 20 events/min conditions).

For the 4-display condition accuracy declined at the extremes but was relatively stable in the mid-range of event rate, indicating that a strategy of favoring speed over accuracy impairs the latter only at the extremes of temporal demand (i.e., changes at the lowest and highest rates of presentation). In the 8-display condition accuracy was relatively stable across event rates until a precipitous decline occurred at the highest level of demand. Hence, a strategy of favoring speed over accuracy did not incur costs for the latter until a threshold of temporal demand was reached. Across the range of event rates faster response was related to a progressive decline in accuracy only in the

1-display conditions. In the other conditions the decline in accuracy either did not occur at lower event rates or was more gradual until the higher levels of information rate.

With respect to changes in information structure, participants responded to increased task load by slowing their responding. This strategy preserved accuracy at lower levels of temporal and structural demand, but at the higher levels of demand accuracy declined substantially and response times showed a corresponding linear increase. Thus, a strategy shift favoring speed was adopted to cope with increased temporal demand but slower response times were not effective in preserving accuracy as structural demand increased, and the highest levels on both dimensions were associated with the largest changes in performance. It is noteworthy that the increment in response time as a function of display was linear, given that the increase in scanning requirements were larger between the 4- and 8-display conditions than between the 1- and 2- or 2- and 4-display conditions due to the spatial separation of the 2×2 grids. The distances between displays or stimuli to be inspected are known to influence visual search, and it is also an important consideration in display design (Wickens & Hollands, 2000). However, the presence of this physical separation was not sufficient to exert a corresponding non-linear effect on response time. Although non-linearity was observed for performance accuracy, this was not restricted to the 8-display condition and the pattern observed is thus unlikely to be due only to the physical separation of displays in that condition.

It is somewhat surprising that at the highest level of structural demand response time declined linearly as a function of event rate, while accuracy remained relatively stable (although accuracy was low relative to lower levels of structural demand) until the highest event rate. This pattern reflects a supra-additive synergistic interaction (Hancock & Szalma, 2008) for accuracy, because increases in these demands combined to induce larger effects on performance than if they exerted independent effects and were thus simply additive. In contrast, response time was associated with a sub-additive antagonistic interaction (Hancock & Szalma, 2008), such that increasing structural demand increased response time while increasing temporal demand decreased response time. Further, the slope of the function for each dimension increased as a function of the level of demand on the other. This may be an artifact of the specific levels of demand tested (i.e., there may be ranges of task load in which the pattern is reversed). However, the pattern may derive from different strategies of adaptation to structural vs. temporal demands. Participants adapted to higher temporal demand by favoring a strategy of speed, which was relatively effective (in terms of maintaining accuracy) at lower levels of demand but was less effective at the most extreme level. The Dynamic Adaptability Theory does not easily accommodate such strategic shifts in speed and accuracy. However, the broader energetic resource perspective can account for these patterns.

4.2. Data-limited and resource-limited processes

The interactive effects of the task dimensions on speed and accuracy may be explained in terms of the relationship of task demands to the availability of processing resources. Norman and Bobrow (1975) identified regions of task demands that they defined as resource- or data-limited. Levels of demand that are sensitive to the allocation of resources (i.e., ranges of task load in which increased resource allocation results in improved performance) are defined as a resource-limited range. Tasks in which allocation of more resources does not affect performance (or performance declines in spite of increased resource allocation) are defined as being in the data-limited range, because performance is determined by the quality of the information to be processed rather than the allocation of more processing capacity.

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[3] As pointed out by one of the reviewers, it is possible that gradual degradation results from averaging across individuals and that individuals vary in the rate of change and the location of the A_C threshold (and see Szalma, 2008). Although inspection of the individual data in this study did not reveal such a pattern, it nevertheless remains a logical possibility that warrants further empirical evaluation.

Norman and Bobrow (1975) argued that speed–accuracy tradeoffs reflect a resource-limited range, because improvement in accuracy occurs as a result of more resources being allocated to meet task demands, which slows processing time (or, alternatively, resource allocation is decreased permitting speed to increase but impairing accuracy). Cases in which speed and accuracy co-vary positively were interpreted as indicative of a data-limited process, because either both accuracy and speed improve without the additional allocation of resources (based on the assumption that greater resource allocation results in longer processing time) or because performance declines on both measures regardless of any additional effort allocation.

The results of the present study indicate that the task was in the data-limited range across levels of source complexity (response time increased and accuracy declined), and for event rate the task was in the resource-limited range until the highest level of temporal demand, at which point the task entered the data-limited range. However, the effects of one dimension on response time and accuracy depended on the level of the other dimension, complicating an interpretation of each dimension in terms of data-limited vs. resource-limited processing. The pattern of effects is clearer when one considers the throughput measure (i.e., bits of information accurately processed per unit time; Thorne, 2006).

The analysis of the throughput measure revealed independent effects of changes in structural and temporal demand. Increased event rate increased bits per minute processed up to 16 events/min, after which throughput declined (see Fig. 8b). This suggests that the lower event rates were in the resource-limited range, as investment of more capacity improved throughput. However, at the highest level of event rate a decline in throughput was observed, indicating that the task had reached the data-limited range. In contrast, the increase in source complexity (display uncertainty; see Fig. 8a) was related to a decline in throughput, indicating a data-limited range across the levels of source complexity tested. This suggests that the slower response time as a function of display was not the result of greater resource investment, but rather the data-limited constraint that scanning takes longer as the angle of displays to be inspected increases. This was maximized in the 8-display condition, in part because of the aforementioned spatial separation of the two grids to be monitored. That display uncertainty was in the data-limited range was supported by comparison of the performance and the self-report data, which indicated that effort increased as a function of the number of displays to be monitored, but that this allocation of effort did not improve performance.

4.3. Performance–workload relationships

The range of stability in performer response can manifest in the pattern of performance–workload relationships (Oron-Gilad et al., 2008; Szalma, in press). In the present study global workload increased as a function of increases in structural and temporal demands, but the effects of the two task dimensions were independent of one another. In contrast, performance changed as a function of interactive effects. However, performance–workload relationships can be evaluated in these circumstances because for each dimension change in workload was equivalent across levels of the other dimension (e.g., at each level of complexity there was an increase in workload as a function of event rate). For instance, for event rate a performance–workload association was observed for accuracy at the higher levels of demand and a workload insensitivity at lower levels of demand (i.e., performance was relatively stable but workload increased). In contrast, a performance–workload dissociation pattern was obtained for response time, indicating improved performance at the cost of greater perceived workload. Consideration of throughput provides a clearer picture: Performance–workload dissociation occurred from 8 to 16 events/min, after which association was observed. Note that performance–workload associations, performance

insensitivity with increasing workload, and workload insensitivity with decreasing performance are most likely in the data-limited range (greater investment of resources does not improve performance), and dissociations and insensitivities in which workload decreases or performance improves are in the resource-limited range (c.f., Norman & Bobrow, 1975).

With respect to source complexity, performance accuracy–workload association was observed at higher levels of demand, with performance insensitivities (with increased workload) at the lower levels. The latter result can occur when the individual maintains performance at the cost of greater resource investment. For response time performance–workload association was observed for display across levels of temporal demand. Further, evaluation of throughput, combining accuracy and response time, indicated performance–workload association across the range of source complexity, supporting the contention that the structural dimension in this study was entirely in the data-limited range.

4.4. Implications for theories of sustained attention

Although the present study did not employ a typical vigilance task, the results have implications for two theories of sustained attention, the mindlessness theory (Robertson, Manly, Andrade, Baddeley, & Yiend, 1997) and the resource perspective (Parasuraman, Warm, & Dember, 1987). According to the mindlessness view, decrements in sustained attention result from increased automaticity in response over time, manifesting as 'mindless' responding. However, several studies (e.g., Grier et al., 2003; Helton & Warm, 2008) have provided evidence that there is little automaticity in vigilance, and that sustained attention is associated with effortful, compensatory activity.

The results of the present study are consistent with this latter perspective because the lowest correct detection scores were associated with the condition with the highest cognitive demand but also the highest perceived workload and the lowest levels of worry (task unrelated thoughts). This is clearly inconsistent with the mindlessness view, which would predict low workload and high levels of task unrelated thoughts. To be sure, the mindlessness perspective applies to vigilance contexts in which response inhibition is required for relatively simple cognitive tasks, and the task demands are primarily attentional. In the present study, however, the task required both maintaining attention and more complex cognitive processing to discriminate signal from non-signal. Hence, the data from this experiment may be limited in its capacity to test the arguments of mindlessness theory. To do so would require manipulating the cognitive demands of the task.

4.5. Implications for the Dynamic Adaptability Theory

One implication of the present results for the Dynamic Adaptability Theory is that it is unlikely that the thresholds of adaptive instability are in the symmetrical hemispherical form shown in Fig. 3, but that they are instead irregular in shape. A second implication is that the zone of psychological adaptation, which has always been interpreted in terms of 'performance,' may need to be divided into two regions, one relating to speed and the other to accuracy. This is because the form of performance change as a function of information structure and information rate depended on the performance measure used. Further, the model needs to account for ranges of information demand in which performance improves or speed–accuracy tradeoffs occur. An alternative to creating two regions of psychological adaptability is to use derived measures such as throughput to evaluate the stability of performance. However, regardless of how the outcome measures are represented, a complication for modification of the model is that the pattern of adaptive response may be different for the two task dimensions, as was the case in this study.

Although the evidence from this study suggests that some aspects of the theory may need to be reconsidered (i.e., the nested structure of adaptive failure and the shape of the adaptive functions; the stability of adaptation; and the relationship between the two task dimensions), it is important to note that Hancock and Warm (1989) did not assert that the symmetry and common forms of the adaptive functions shown in Figs. 2 and 3 *must* exist, that the distances between thresholds *must* be equivalent, or that the level of adaptation is literally flat (indeed, they noted the potential value of chaos and catastrophe theory representations in modeling local maxima and minima in adaptive response). Rather, they viewed the model presented in Figs. 2 and 3 as an initial step to be followed by modifications based on empirical and theoretical developments. The present study provides evidence to support such modification, particularly in the patterns of performance, workload, and stress as a function of information structure and rate.

In contrast to performance, the pattern of results for perceived workload seemed to generally conform to the model, in that as demands increased (on both dimensions) perceived workload increased. This pattern was also observed for distress, but perceived task-engagement showed a relative insensitivity to task demand, even increasing somewhat as a function of event rate at the lowest level of structural demand. For the third stress dimension, worry, stress actually *decreased* as a function of display demand. Across subjective measures results suggest that participants responded to higher demands by maintaining or increasing effort, but at greater subjective cost. Cases in which performance remains stable or even increases would correspond to the region A_C–A_ψ in Fig. 2. When performance is also impaired, the pattern manifests in the region A_ψ–A_P.

4.5.1. The (dynamic) stability of adaptation

The small but significant linear trends observed in this study at the lowest levels of information demand suggest that the plateau shown in Fig. 2 may not represent absolute stability, but rather consist of small changes in adaptive response across the range of input stress, with local maxima (perhaps even improvement in performance) and minima and regions of transient or 'local' plateaus (e.g., correct detections in the 4-display condition; see Fig. 5a) driving the specific adaptive state of a person at a particular level of task demand. The results also suggest that even in these plateau regions there may be gradual declines in adaptation (c.f., Hockey, 1997, 2003). For instance, even at the lowest levels of demand (1 display, 8–12 events/min) there was a decline in performance accuracy and an increase in workload (see Fig. 9a), indicating small but statistically reliable changes in adaptive response.

Recall that the dynamic adaptability theory identifies regions of hypo and hyper stress. In their original conception, Hancock and Warm (1989) identified vigilance as an instance of the former. However, a large body of work has shown that vigilance imposes high workload and is stressful (Warm, Dember, & Hancock, 1996), which indicates that in many instances vigilance tasks (and perhaps signal detection in general) reside in the hyper stress region. Although it may be possible that there are tasks in which vigilance and signal detection are in the hypostress regions (e.g., a low event rate, single display) the present results indicated low workload/stress and high performance under these conditions. However, this study employed rather short task durations (12 min) and a cognitively demanding discrimination, and it is not clear this pattern of results would extend to longer task durations or to easier signal/non-signal discriminations. Future theoretical and empirical efforts should distinguish between the demands for cognitive processing stimuli versus to requirement to maintain attention. That is, potential differences in the relationships of task dimensions to the discrimination versus the sustained attention requirements of the task should be evaluated. These different forms of demand may exhibit distinct ranges of 'hypo' and 'hyper' stress.

Note that Hancock and Warm (1989) conceived of hyper and hypo stress as *task* demands, i.e., as deterministic task loads, rather than the *adaptive response* of the individual. Thus, the high workload and stress associated with vigilance reflects compensatory response by the performer to deal either with overload (as in the case of an extremely high event rate; e.g., see Helton & Warm, 2008) or underload (e.g., the finding that even low event rates or single displays are associated with perceived workload scores in the middle of the scale; Galinsky, Dember, & Warm, 1989; cited in Warm et al., 1996; Grubb et al., 1995). Although the task load and the adaptive response are *conceptually* distinct, a problem for Dynamic Adaptability Theory and stress research generally is to *empirically* distinguish these constructs. Such distinctions may avoid circularity in defining hypo/hyper stress (i.e., defining a strong compensatory response as hyper stress and a weak response – e.g., low perceived workload – as hypo stress), but a unit of measure of the environmental demands is necessary to achieve clear empirical distinction of input and adaptive response. Indeed, it may be that ranges of hypo or hyper stress are specifiable only in the context of cognitive appraisals by the performer (Lazarus, 1999; Matthews et al., 2002). The transactional approach to stress (Lazarus, 1999; Matthews, 2001) argues that the unit of analysis should be the *transaction* between the input and response, but to date this has not been articulated with sufficient precision to identify the relations at the 'microcognitive' (Crandall, Klein, & Hoffman, 2006) level of analysis.

4.5.2. Task dimensions

According to DAT the two information dimensions should have interactive effects. However, in this study interactions were observed for performance but not for subjective state. These results raise the possibility that whether the information dimensions interact to influence adaptive response may depend on the specific range of information demand and the form of adaptive response. Future research should examine the relationships between these dimensions using these manipulations with other kinds of information processing tasks and using manipulations other than display uncertainty and event rate.

A broader issue that Hancock and Warm (1989) themselves raised is the quantification of information structure and rate. In this study these dimensions were operationalized as display uncertainty and event rate, respectively. Hancock and Caird (1993) manipulated these dimensions in terms of distance to target goal and time available for action. The relationship between the two dimensions may depend in part on how they are quantified. For instance, one can manipulate information structure by varying spatial uncertainty, the number of steps required to complete a task, or the working memory capacity required. Information rate may be manipulated by varying stimulus duration or temporal uncertainty (for reviews see Davies & Parasuraman, 1982; Warm & Jerison, 1984).

However, quantifying information in complex tasks with multiple components of structure and rate may be difficult. It is theoretically possible to combine multiple forms of information structure or information rate, and to combine these two dimensions using the vector approach advocated by Hancock and Warm (1989), but it is unclear how the multiple variables should be combined (i.e., additively or multiplicatively). Efforts to develop a vector model would be facilitated by the development of a common 'adaptation scale' for comparison of different forms of response (e.g., correct detections vs. perceived workload). Nevertheless, accurate modeling of the effects of multiple stressors is a problem for all theories of stress and performance (Hancock & Szalma, 2008), and the quantification of information processing is a challenge for most cognitive theories in psychology (McBride & Schmorrow, 2005). Development of an approach to combining these elements (e.g., a vector representation) would be a substantial theoretical advance for theories of stress and performance.

5. Summary and conclusions

The present study tested elements of the dynamic adaptability theory of Hancock and Warm (1989). Results were broadly consistent with the model, but as Hancock and Warm (1989) themselves noted, structural modification of the model may be necessary. These include recognition that the widths of the zones of adaptability may vary across contexts (even approaching zero in some cases), and that the zone of psychological adaptability needs to be modified to account for differences across performance measures (i.e., accuracy, response time) and to also account for increased performance quality. However, the greatest challenges to this theory, and perhaps to all cognitive and energetic theories of performance, are the quantification of attentional resources and of information processing (c.f., McBride & Schmorrow, 2005). The utility of the Dynamic Adaptability Theory will be constrained by whether valid measures of information structure and rate can be derived, and whether the precision of the resource metaphor can be improved (Hancock & Szalma, 2007; Szalma & Hancock, 2007). This may prove to be particularly difficult in performance settings in which there are multiple components constituting each dimension. Whether the vector representation advocated by Hancock and Warm (1989) can adequately address this issue is a matter for further empirical research and theoretical refinement.

References

Benjamins, J. S., Hooge, I. T. C., van Elst, J. C., Wertheim, A. H., & Verstraten, F. A. J. (2009). Search time critically depends on irrelevant subset size in visual search. *Vision Research*, 49, 398–406.

Cameron, E. L., Tai, J. C., Eckstein, M. P., & Carrasco, M. (2004). Signal detection theory applied to three visual search tasks—Identification, yes/no detection and localization. *Spatial Vision*, 17, 295–325.

Conway, G., Szalma, J. L., & Hancock, P. A. (2007). A quantitative meta-analytic examination of whole-body vibration effects on human performance. *Ergonomics*, 50, 228–245.

Crandall, B., Klein, G., & Hoffman, R. R. (2006). *Working minds: A practitioner's guide to cognitive task analysis*. Cambridge, MA: MIT Press.

Davies, D. R., & Parasuraman, R. (1982). *The psychology of vigilance*. London: Academic Press.

Galinsky, T. L., Dember, W. N., & Warm, J. S. (1989, March). Effects of event rate on subjective workload in vigilance performance. *Paper presented at the Southern Society for Philosophy and Psychology*.

Grier, R. R., Warm, J. S., Dember, W. N., Matthews, G., Galinsky, T. L., Szalma, J. L., et al. (2003). The vigilance decrement reflects limitations in effortful attention, not mindlessness. *Human Factors*, 45, 349–359.

Grubb, P. L., Warm, J. S., Dember, W. N., & Berch, D. B. (1995). Effects of multiple signal discrimination on vigilance performance and perceived workload. *Proceedings of the Human Factors and Ergonomics Society*, 39, 1360–1364.

Hancock, P. A. (1996). Effects of control order, augmented feedback, input device and practice on tracking performance and perceived workload. *Ergonomics*, 39, 1146–1162.

Hancock, P. A., & Caird, J. K. (1993). Experimental evaluation of a model of mental workload. *Human Factors*, 35, 413–429.

Hancock, P. A., Ross, J. M., & Szalma, J. L. (2007). A meta-analysis of performance response under thermal stressors. *Human Factors*, 49, 851–877.

Hancock, P. A., & Szalma, J. L. (2007). Stress and neuroergonomics. In R. Parasuraman, & M. Rizzo (Eds.), *Neuroergonomics: The brain at work* (pp. 195–206). Oxford: Oxford University Press.

Hancock, P. A., & Szalma, J. L. (2008). Stress and performance. In P. A. Hancock, & J. L. Szalma (Eds.), *Performance under stress* (pp. 1–18). Hampshire, UK: Ashgate.

Hancock, P. A., & Warm, J. S. (1989). A dynamic model of stress and sustained attention. *Human Factors*, 31, 519–537.

Harris, W. C., Hancock, P. A., & Harris, S. C. (2005). Information processing changes following extended stress. *Military Psychology*, 17, 15–128.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock, & M. Najmedin (Eds.), *Human mental workload* (pp. 139–183). Oxford, England: North-Holland.

Hebb, D. O. (1955). Drives and the C.N.S. (conceptual nervous system). *Psychological Review*, 62, 243–254.

Helton, W. S., Matthews, G., & Warm, J. S. (2010). Stress state mediation between environmental variables and performance: The case of noise and vigilance. *Acta Psychologica*, 130, 204–213.

Helton, W. S., & Warm, J. S. (2008). Signal salience and the mindlessness theory of vigilance. *Acta Psychologica*, 129, 18–25.

Hockey, R. (1984). Varieties of attentional state: The effects of environment. In R. Parasuraman, & D. R. Davies (Eds.), *Varieties of attention* (pp. 449–483). New York: Academic Press.

Hockey, G. R. J. (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive–energetical framework. *Biological Psychology*, 45, 73–93.

Hockey, G. R. J. (2003). Operator functional state as a framework for the assessment of performance. In A. W. K. Gaillard, G. R. J. Hockey, & O. Burov (Eds.), *Operator functional state: The assessment and prediction of human performance degradation in complex tasks* (pp. 8–23). Amsterdam: IOS Press.

Hockey, G. R. J., Gaillard, A. W. K., & Coles, M. G. H. (Eds.). (1986). *Energetic aspects of human information processing*. The Netherlands: Nijhoff.

Hockey, R., & Hamilton, P. (1983). The cognitive patterning of stress states. In G. R. J. Hockey (Ed.), *Stress and fatigue in human performance* (pp. 331–362). Chichester: Wiley.

Jerison, H. J., & Pickett, R. M. (1964). Vigilance: The importance of the elicited observing processes in vigilance. *Science*, 143, 970–971.

Lamiell, J. T. (2003). *Beyond individual and group differences: Human individuality, scientific psychology, and William Stern's Critical Personalism*. Thousand Oaks, CA: Sage.

Lanzetta, T. M., Dember, W. N., Warm, J. S., & Berch, D. B. (1987). Effects of task type and stimulus homogeneity on the event rate function in sustained attention. *Human Factors*, 29, 625–633.

Lazarus, R. S. (1999). *Stress and emotion: A new synthesis*. New York: Springer.

Lazarus, R. S., & Folkman, S. (1984). *Stress, appraisal, and coping*. New York: Springer Verlag.

Loeb, M., & Binford, J. R. (1968). Variation in performance on auditory and visual monitoring tasks as a function of signal and stimulus frequencies. *Perception & Psychophysics*, 4, 361–367.

Matthews, G. (2001). Levels of transaction: A cognitive science framework for operator stress. In P. A. Hancock, & P. A. Desmond (Eds.), *Stress, workload, and fatigue* (pp. 5–33). Mahwah, NJ: Erlbaum.

Matthews, G., Campbell, S. E., Falconer, S., Joyner, L. A., Huggins, J., Gilliland, K., et al. (2002). Fundamental dimensions of subjective state in performance settings: Task engagement, distress, and worry. *Emotion*, 2, 315–340.

Matthews, G., Joyner, L., Gilliland, K., Campbell, S., Falconer, S., & Huggins, J. (1999). Validation of a comprehensive stress state questionnaire: Towards a state 'big three'? In I. J. Deary, I. Mervielde, F. De Fruyt, & F. Ostendorf (Eds.), *Personality Psychology in Europe*, 7. (pp. 335–350)Tilburg, the Netherlands: Tilburg University Press.

Maxwell, S. E., & Delaney, H. D. (2004). *Designing experiments and analyzing data: A model comparison perspective* (2nd ed). Mahwah, NJ: Erlbaum.

McBride, D. K., & Schmorrow, D. (Eds.). (2005). *Quantifying human information processing*. Lanham, MD: Lexington Books.

Norman, D., & Bobrow, D. (1975). On data-limited and resource-limited processing. *Journal of Cognitive Psychology*, 7, 44–60.

Oron-Gilad, T., Szalma, J. L., Stafford, S. C., & Hancock, P. A. (2008). The workload and performance relationship in the real world: A study of police officers in a field shooting exercise. *International Journal of Occupational Safety and Ergonomics*, 14, 119–131.

Parasuraman, R. (1979). Memory load and event rate control sensitivity decrements in sustained attention. *Science*, 205, 924–927.

Parasuraman, R., & Hancock, P. A. (2001). Adaptive control of mental workload. In P. A. Hancock, & P. A. Desmond (Eds.), *Stress, workload, and fatigue* (pp. 305–320). Mahwah, NJ: Erlbaum.

Parasuraman, R., Warm, J. S., & Dember, W. N. (1987). Vigilance: Taxonomy and utility. In J. S. Warm, L. S. Mark, & R. L. Houston (Eds.), *Ergonomics and human factors: Recent research* (pp. 11–32). New York: Springer-Verlag.

Pavlovskaya, M., Ring, H., Groswasser, Z., Keren, O., & Hochstein, S. (2001). Visual search in peripheral vision: Learning effects and set-size dependence. *Spatial Vision*, 14, 151–173.

Pedhazur, E. J. (1997). *Multiple regression in behavioral research* (3rd ed). Harcourt Brace: Orlando, FL.

Reid, G. B., & Nygren, T. E. (1988). The subjective workload assessment technique: A scaling procedure for the measuring of mental workload. In P. A. Hancock, & N. Meshkati (Eds.), *Human mental workload* (pp. 185–218). Amsterdam: North-Holland.

Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). "Oops!": Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia*, 35, 747–758.

Selye, H. (1976). *The stress of life* (Revised edition). New York: McGraw-Hill.

Szalma, J. L. (2008). Individual differences in stress reaction. In P. A. Hancock, & J. L. Szalma (Eds.), *Performance under stress* (pp. 323–357). Aldershot, Hampshire, UK: Ashgate.

Szalma, J.L. (in press). Individual differences in stress, fatigue, and performance. In: P.A. Desmond, G. Matthews, and P.A. Hancock (Eds.), *The handbook of operator fatigue*. Aldershot, Hampshire, UK: Ashgate.

Szalma, J. L., & Hancock, P. A. (2007). Task loading and stress in human–computer interaction: Theoretical frameworks and mitigation strategies. In J. A. Jacko, & A. Sears (Eds.), *Handbook for human–computer interaction in interactive systems* (pp. 115–132). (2nd Ed.). New York: Erlbaum Taylor & Francis Group.

Szalma, J. L., & Hancock, P. A. (2011). Noise effects on human performance: A meta-analytic synthesis. *Psychological Bulletin*, 137, 682–707.

Taub, H. A., & Osborne, H. (1968). Effects of signal and stimulus rates on vigilance performance. *The Journal of Applied Psychology*, 52, 133–138.

Thorne, D. R. (2006). Throughput: A simple performance index with desirable characteristics. *Behavior Research Methods*, 38, 569–573.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 97–136.

Warm, J. S., Dember, W. N., & Hancock, P. A. (1996). Vigilance and workload in automated systems. In R. Parasuraman, & M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 183–200). Hillsdale, NJ: Erlbaum.

Warm, J. S., Howe, S. R., Fishbein, H. D., Dember, W. N., & Sprague, R. L. (1984). Cognitive demand and the vigilance decrement. In A. Mital (Ed.), *Trends in ergonomics/human factors I* (pp. 15–20). North Holland: Elsevier.

Warm, J. S., & Jerison, H. J. (1984). The psychophysics of vigilance. In J. S. Warm (Ed.), *Sustained attention in human performance* (pp. 15–59). Chichester, United Kingdom: Wiley.

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd ed). Upper Saddle River, NJ: Prentice-Hall.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review, 1*, 202–238.

Wolfe, J. M., Horowitz, T. S., & Kenner, N. M. (2005). Rare items often missed in visual searches. *Nature, 435*, 439–440.

Wolfe, J. M., Horowitz, T. S., Van Wert, M. J., Kenner, N. M., Place, S. S., & Kibbi, N. (2007). Low target prevalence is a stubborn source of errors in visual search tasks. *Journal of Experimental Psychology. General, 136*, 623–638.

Yeh, Y., & Wickens, C. D. (1988). Dissociation of performance and subjective measures of workload. *Human Factors, 30*, 111–120.