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# A Neuroergonomics Approach to Mental Workload, Engagement and Human Performance

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The assessment and prediction of cognitive performance is a key issue for any discipline concerned with human operators in the context of safety-critical behavior. Most of the research has focused on the measurement of mental workload but this construct remains difficult to operationalize despite decades of research on the topic. Recent advances in Neuroergonomics have expanded our understanding of neurocognitive processes across different operational domains. We provide a framework to disentangle those neural mechanisms that underpin the relationship between task demand, arousal, mental workload and human performance. This approach advocates targeting those specific mental states that precede a reduction of performance efficacy. A number of undesirable neurocognitive states (mind wandering, effort withdrawal, perseveration, inattentive phenomena) are identified and mapped within a two-dimensional conceptual space encompassing task engagement and arousal. We argue that monitoring the prefrontal cortex and its deactivation can index a generic shift from a nominal operational state to an impaired one where performance is likely to degrade. Neurophysiological, physiological and behavioral markers that specifically account for these states are identified. We then propose a typology of neuroadaptive countermeasures to mitigate these undesirable mental states.

**Keywords:** neuroergonomics, performance prediction, degraded attentional and executive mental states, task engagement, mental workload

## INTRODUCTION

A study of mental workload is fundamental to understanding the intrinsic limitations of the human information processing system. This area of research is also crucial for investigation of complex teaming relationships especially when interaction with technology necessitates multitasking or a degree of cognitive complexity.

## The Growth of Mental Workload

Mental workload has a long association with human factors research into safety-critical performance (Moray, 1979; O'Donnell and Eggemeier, 1986; Hancock and Meshkati, 1988; Hancock and Desmond, 2001; Wickens and Tsang, 2014; Young et al., 2015). Forty years have passed since the publication of the seminal collection edited by Moray (1979) and the study of mental workload remains an active topic in contemporary human factors research; a keyword

search based on Google Scholar listed more than 200,000 articles published on the topic since 2000, see also Table 1 in Young et al. (2015). The significance of human mental workload for those technological trends that are forecast during the second machine age (Brynjolfsson and McAfee, 2014) guarantees its importance for human factors research in future decades.

The lineage of mental workload incorporates a number of theoretical perspectives, some of which precede the formalization of the concept itself. Early work linking physiological activation to the prediction of performance (Yerkes and Dodson, 1908; Duffy, 1962) was formalized into an energetical model of attentional resources (Kahneman, 1973) that emphasized a dynamic relationship between finite information processing capacity and variable cognitive demands (Norman and Bobrow, 1975; Navon and Gopher, 1979; Wickens, 1980). The descriptive quality of the early work on attentional resources was sharpened by cognitive models of control (Broadbent, 1971; Schneider et al., 1984; Shallice and Burgess, 1993). Hybrid frameworks that place cognitive processes within a resource framework have been hugely influential in the field, such as the multiple resource model (Wickens, 1984, 2002, 2008; Wickens and Liu, 1988) whereas others introduced agentic features, such as dynamic self-regulation and adaptation, within models of human performance (Hockey et al., 1986; Hockey, 1997). For instance, Hancock and Warm (1989)'s dynamic adaptive theory (DAT) postulates that the brain seeks resource homeostasis and cognitive comfort. However, environmental stressors can progressively shift individual's adaptive abilities from stability to instability depending on one's cognitive and psychological resources. The DAT is an extension of the Yerkes and Dodson inverted-U law, in a sense that very low (hypostress) and very high (hyperstress) task demands can both degrade the adaptability and consequently impair performance. All these perspectives are united by a characterization of the human information processing system as a finite resource with limited capacity (Kramer and Spinks, 1991).

## Mental Workload Measurement

Research into the measurement of mental workload has outstripped the development of theoretical frameworks. Measures of mental workload can be categorized as performance-based, or linked to the process of subjective self-assessment, or associated with psychophysiology or neurophysiology. Each category has specific strengths and weaknesses (O'Donnell and Eggemeier, 1986; Wierwille and Eggemeier, 1993) and the sensitivity of each measurement type can vary depending on the level of workload experienced by the operator (De Waard, 1996). The development of multidimensional measures led inevitably to an inclusive framework for mental workload. The cost of this integration is dissociation between different measures of mental workload, e.g., Yeh and Wickens (1988), and an integrated workload concept that remains poorly defined from a psychometric perspective (Matthews et al., 2015).

There are a number of reasons that explain why mental workload is easy to quantify but difficult to operationalize. The absence of a unified framework for human mental workload, its antecedents, processes and measures has generated a highly

abstract concept, loosely operationalized and supported by a growing database of inconsistent findings (Van Acker et al., 2018). The absence of a general explanatory model is complicated by the fact that mental workload, like stress and fatigue (Matthews, 2002), is a transactional concept representing an interaction between the capacities of the individual and the specific demands of a particular task. Within this transactional framework, mental workload represents a confluence between inter-individual sources of trait variability (e.g., skill, IQ, personality), intra-individual variation (e.g., emotional states, motivation, fatigue), and the specific configuration of the task under investigation (see also Table 2 in Van Acker et al., 2018).

For the discipline of human factors, the study of mental workload serves two primary functions: (a) to quantify the transaction between operators and a range of task demands or technological systems or operational protocols, and (b) to predict the probability of performance impairment during operational scenarios, which may be safety-critical. One challenge facing the field is delineating a consistent relationship between mental workload measurement and performance quality on the basis of complex interactions between the person and the task. The second challenge pertains to the legacy and utility of limited capacity of resources as a framework for understanding those interactions.

In the following sections, we detail some limitations of mental resources and advocate the adoption of a neuroergonomic approach (Sarter and Sarter, 2003; Parasuraman and Rizzo, 2008; Parasuraman and Wilson, 2008; Mehta and Parasuraman, 2013; Ayaz and Dehais, 2018) for the study of mental workload and human performance. The neuroergonomic framework emphasizes a shift from limited cognitive resources to characterizing impaired human performance and associated states with respect to neurobiological mechanisms.

## Toward a Limit of the Theory of Limited Resources

The concept of resources represents a foundational challenge to the development of a unified framework for mental workload and prediction of human performance. The conception of a limited capacity for information processing is an intuitive one and has been embedded within several successful models, e.g., multiple resources (Wickens, 2002). But this notion has always been problematic because resources are a general-purpose metaphor with limited explanatory powers (Navon, 1984) that incorporate both cognitive processes (e.g., attention, memory) and energetical constructs (e.g., mental effort) in ways that are difficult to delineate or operationalize. The allegorical basis of resources almost guarantees an abstract level of explanation (Van Acker et al., 2018) that is accompanied by divergent (Matthews et al., 2015), and sometimes contradictory operationalizations (Yeh and Wickens, 1988; Annett, 2002).

For example, the theory of limited cognitive resources predicts that exposure to task demands that are sustained and demanding can impair performance due to resource depletion via self-regulation mechanisms at the neuron-level (i.e., local-sleep state theory, see Van Dongen et al., 2011) or compromise access to

resources mechanisms (Borrigan Pedraz and Peigneux, 2016). However, this type of explanation fails to clarify why non-challenging tasks, such as passive monitoring (Matthews et al., 2002, 2010) can promote episodes of mind wandering whereby attention drifts from task-related to task-irrelevant thoughts (Smallwood et al., 2008; Durantin et al., 2015; Smallwood and Schooler, 2015). Although some propositions, such as the theory of “malleable resources” (Young and Stanton, 2002), have intuited this paradox, this theory is at a highly descriptive level and remains difficult to operationalize.

Similarly, the occurrence of stressful and unexpected operational scenarios is known to impair executive functioning and provoke perseveration, see Dehais et al. (2019) for review. Perseveration is defined as a tendency to continue an action after cessation of the original stimulation, which is no longer relevant to the goal at hand (Sandson and Albert, 1984). For example, several studies conducted on emergency evacuation situations reported irrational and perseverative behaviors even when tasks were simple and undemanding (Proulx, 2001; Kobes et al., 2010). A paradigmatic situation is the one in which people fail to escape from fire because they push the door instead of pulling it. Perseveration can also have devastating consequences during safety-critical tasks, such as aviation (O’Hare and Smitheram, 1995; Orasanu et al., 1998; Reynal et al., 2017) and in the medical domain (Bromiley, 2008). This category of performance impairment cannot be explained solely through the prism of limited mental resources. Operators who persist with an erroneous strategy, such as an aircrew who attempt to land their craft at all costs despite bad weather conditions, are generally capable of performing the required actions and tend to invest greater effort even as their task goal becomes difficult or even impossible to achieve (Dehais et al., 2010, 2012).

The concept of limited cognitive resources could explain failures of attention such as inattention blindness (Brand-D’Abrescia and Lavie, 2008) or deafness (Raveh and Lavie, 2015). Both categories describe an inability to detect unexpected stimuli, such as alarms from the interface (Dehais et al., 2011, 2014), and represent breakdown of selective attention due to the presence of competing demands on the human information processing system. It has been demonstrated that individuals with greater information processing capacity (i.e., higher working memory span) exhibit superior ability with respect to divided and sustained attention (Colflesh and Conway, 2007; Unsworth and Engle, 2007), and therefore, should be less susceptible to the effects of inattention during the performance of demanding tasks. However, this hypothesis is contradicted by the absence of any correlation between individual differences in processing capacity and the occurrence of inattention blindness (Bredemeier and Simons, 2012; Beanland and Chan, 2016; Kreitz et al., 2016a) or deafness (Kreitz et al., 2016b; Dehais et al., 2019).

This research suggests that the limited resource model cannot account for critical lapses of attention and executive functioning that are observed under conditions of high mental workload. Therefore, we must go beyond the limitations of the resource concept as an explanatory model of mental workload and turn our attention to the neural underpinnings of attention and behavior (Parasuraman et al., 1999).

## RESOURCES: A NEUROERGONOMIC PERSPECTIVE

The last three decades have witnessed a revolution in our understanding of neural mechanisms that are fundamental to attention and human performance. Progress in the field has been driven by the development of advanced and portable neuroimaging techniques, which permit non-invasive examination of the “brain at work.” Neuroergonomics is a multidisciplinary field born from these technical innovations that is broadly defined as the study of the human brain in relation to performance at work and in everyday settings (Parasuraman and Rizzo, 2008). The goal of this field is to integrate both theories and principles from ergonomics, neuroscience and human factors in order to provide insights into the relationship between brain function and behavioral outcomes in the context of work and everyday life (Rizzo et al., 2007; Parasuraman and Rizzo, 2008; Parasuraman and Wilson, 2008; Lees et al., 2010; Ayaz and Dehais, 2018).

### The Multiple Biological Substrates of Mental Resources

The incorporation of neurophysiological measures of mental workload offers a reductive pathway to the reification of resources and those neurobiological states associated with impaired performance. At a fundamental level, the functioning of neurons within the brain is a form of limited resource (Beatty, 1986), requiring oxygen and glucose to generate cellular energy in the form of adenosine triphosphate (ATP) while having a very limited capacity to store these energy substrates (Saravini, 1999). The same logic holds for ions (e.g., potassium, calcium, sodium) that play a key role in nerve impulses. It is also reasonable to consider neural networks as resources with respect to their supporting glial cells (e.g., astrocytes), which ensure the processing of information (Mandrick et al., 2016). Understanding the interactions between neurobiological resources with reference to fundamental processes in brain physiology represents a crucial approach within neuroergonomic analysis of mental workload (Parasuraman and Rizzo, 2008; Ayaz and Dehais, 2018).

### Brain and Inhibitory Mechanisms

The brain must be considered to be a “noisy” organ, whereby assembly of neurons are constantly responsive to environmental stimulations, see Pandemonium architecture as an early example, such as Selfridge (1959). Inhibitory mechanisms are implemented to cancel out cerebral noise by mitigating the activation of distracting neuronal assemblies (Polich, 2007). This process may occur at a local level via lateral inhibition, whereby groups of neurons can attenuate the activity of their neighbors in order to be “better heard” (Coultrip et al., 1992). The same mechanism can also take place via top-down regulation, known as inhibitory control, wherein high-level cortical areas (e.g., prefrontal cortex) reduce task- or stimulus-irrelevant neural activities (Munakata et al., 2011). However, these inhibitory mechanisms can also curtail the capacity of the brain to consider new or alternative information, thus leading to perseveration (Dehais et al., 2019).



An appropriate metaphor is to consider a group led by an authoritarian leader who is totally engaged with one specific goal or strategy and does not listen to alternative viewpoints of other members of the group. Within this metaphor, information processing resources are present (i.e., group members) but are disregarded in the presence of an overriding directive (i.e., the leader). In other words, high mental workload leads to impaired performance, not because of limited resources *per se*, but because of those neurological mechanisms designed to prioritize a specific goal or directive.

## The Non-linear Effects of Neuromodulation

The prefrontal cortex (PFC) is a brain structure often identified as the neurophysiological source of limited resources (Posner and Petersen, 1990; Parasuraman, 2003; Ramsey et al., 2004; Modi et al., 2017). The PFC serves a control function during routine cognitive operations, such as: action selection, retrieval/updating in working memory, monitoring and inhibition (Ramnani and Owen, 2004; Ridderinkhof et al., 2004). It is often activated during high levels of cognitive demand (Ayaz et al., 2012; Herff et al., 2014; Racz et al., 2017; Gateau et al., 2018; Fairclough et al., 2019) and dysfunction of this structure is known to degrade performance (Sandson and Albert, 1984; Dolcos and McCarthy, 2006). However, the PFC is complex and its function is subject to the quadratic influence of neuromodulation via the influence of noradrenaline and dopamine (Arnsten, 2009; Arnsten et al., 2012). Noradrenaline is associated with the mediation of arousal (Chrousos, 2009) whereas dopamine is involved in the processing of reward with regard to the ongoing tasks (Schultz, 2002). Both catecholamines exert an inverted-U relationship with the PFC neurons (Vijayraghavan et al., 2007; Robbins and Arnsten, 2009), a reduction of these neurochemicals will depress the firing rate of noradrenergic and dopaminergic PFC neurons (see **Figure 1**). This mechanism may explain why unstimulating and non-rewarding tasks (e.g., passive supervisory control over a sustained period) can inhibit executive functioning and induce mind wandering. Conversely, excessive levels can also have a deleterious effect by suppressing PFC neuron firing rate (Birnbau et al., 1999). In addition to decreasing the activity of the PFC, dopamine and noradrenaline activate subcortical areas, such as basal ganglia, that trigger automated schemes and initiate automatic responses (Wickens et al., 2007). These automated behaviors have an advantage of speed compared to flexible but slower behaviors generated by the prefrontal cortex (Dolan, 2002). This neurological switch from prefrontal to subcortical areas, is presumed to derive from the early age of humanity to ensure survival (Arnsten, 2009). In modern times, it manifests itself as a process of defaulting to well-learned behaviors, which are effective for only operational situations that are simple and familiar. This is the mechanism that promotes perseveration (Dehais et al., 2019) in task scenarios that are complex and novel (Staal, 2004; Ellenbogen et al., 2006) or offer intrinsic, short-term rewards, e.g., landing at all costs after a long transatlantic flight (Causse et al., 2013). These fundamental neurological mechanisms illustrate that impaired operational

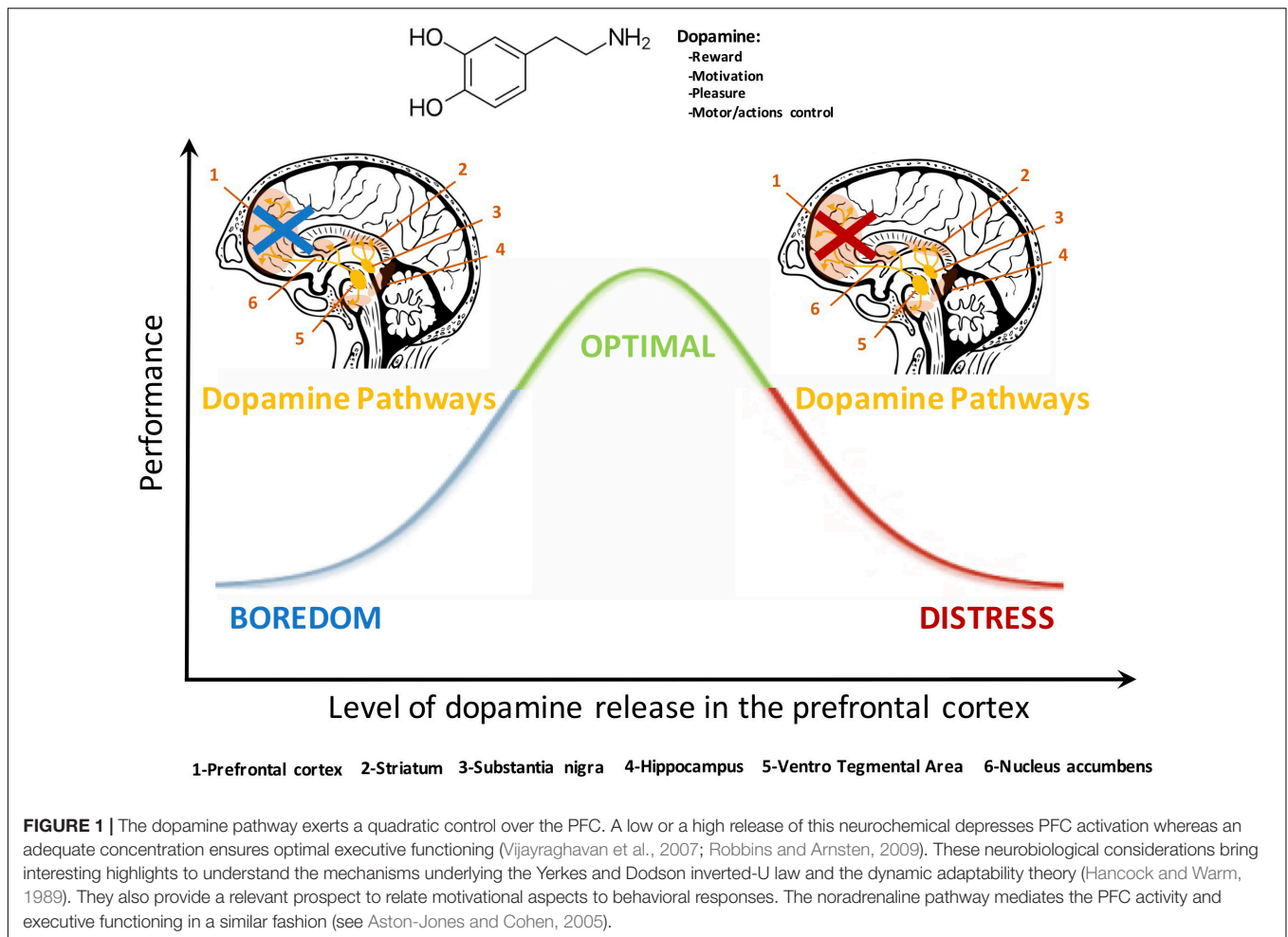
performance cannot be simply explained in terms of limited resources, such as a concentration of dopamine, but must be viewed from a neuroergonomic perspective that emphasizes the complexity of interactions between brain areas that evolved over thousands of years.

## Attentional Dynamics and Dominance Effects

The existence of information processing resources can also be conceptualized as functional attentional networks in the brain. Michael Posner was the first to pioneer a network approach to the operationalization of resources in the early days of neuroimaging (Posner and Tudela, 1997). His influential analysis (Posner and Petersen, 1990; Posner and Dehaene, 1994; Petersen and Posner, 2012; Posner, 2012) described how specific networks were dedicated to the particular functions of attentional regulation, e.g., alerting, orientation, focus. This conceptualization developed into the delineation of a dorsal fronto-parietal network (e.g., intraparietal cortex, superior frontal cortex) that supports focused attention on specific task-relevant stimuli and a corresponding ventral fronto-parietal network (e.g., temporo-parietal cortex, inferior frontal cortex) in the right hemisphere, which activates in a bottom-up fashion to reorientate attention to interruptive stimuli (Corbetta and Shulman, 2002; Corbetta et al., 2008). Under nominal conditions, interaction between the dorsal and the ventral pathways ensure optimal trade-off between those attentional strategies associated with exploitation and exploration. However, under conditions of high task demand or stress or fatigue, this mechanism may become biased toward dominance of the dorsal over the ventral network, leading to attentional phenomena associated with inflexibility (Todd et al., 2005; Durantin et al., 2017; Edworthy et al., 2018; Dehais et al., 2019a). A similar dynamic of bias and dominance is apparent in the relationship between the dorsal and ventral pathways and the default mode network (Andrews-Hanna et al., 2014), which is associated with mind-wandering, spontaneous thoughts and disengagement from task-related stimuli (Fox et al., 2015).

## Performance Monitoring and Effort Withdrawal

The capacity of the brain to monitor performance quality and progress toward task goals is another important function of the PFC during operational performance. The posterior medial frontal cortex (pmMFC) is a central hub in a wider network devoted to performance monitoring, action selection and adaptive behavior (Ullsperger et al., 2014; Ninomiya et al., 2018). The pmMFC is sensitive to error and failure to achieve a task goal (Ullsperger et al., 2007); the detection of failure represents an important cue for compensatory strategies, such as increased investment of mental effort (Hockey, 1997). This network is particularly important when the level of task demand experienced by the operator is associated with a high rate of error and increased probability of failure. The model of motivational intensity (Richter et al., 2016) predicts that effort is withdrawn from task performance if success likelihood is appraised to be



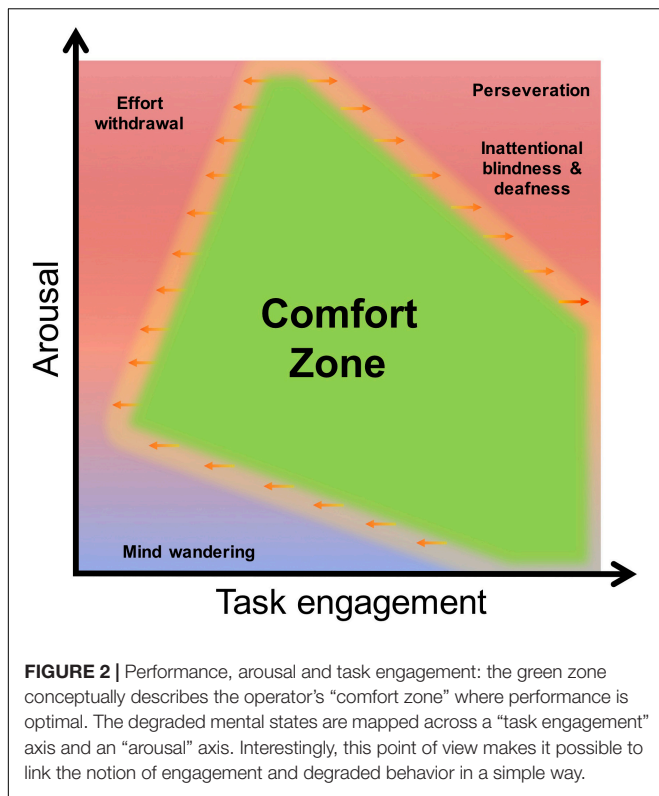
very low (Hopstaken et al., 2015); similarly, models of behavioral self-regulation (Carver and Scheier, 2000) argue that task goals can be adjusted downward (i.e., lower levels of performance are tolerated as acceptable) or even abandoned if goal attainment is perceived to be impossible. There is evidence that increased likelihood of failure is associated with deactivation of the PFC (Durantin et al., 2014; Ewing et al., 2016; Fairclough et al., 2019), for operational performance where failure can often jeopardize the safety of oneself and others, increased likelihood of failure can also provoke strong emotional responses that are associated with stress and cognitive interference (Sarason et al., 1990), which can function as distractors from task activity in their own right (Dolcos and McCarthy, 2006; Qin et al., 2009; Gärtner et al., 2014).

This neuroergonomic approach provides a biological basis upon which to develop a concept of limited human information processing, with respect to competing neurological mechanisms, the influence of neuromodulation in the prefrontal cortex and antagonist directives between different functional networks in the brain. The prominence of inhibitory control coupled with competition between these neural networks delineate a different category of performance limitations during extremes of low vs. high mental workload,

i.e., simultaneous activation of functional networks with biases toward mutually exclusive stimuli (external vs. internal) or contradictory directives (focal attention vs. reorientation of attention).

## UNDERSTANDING PERFORMANCE RELATED MENTAL STATES

The previous sections have highlighted the complexity of those brain dynamics and networks that can introduce inherent limitations on human information processing. On the basis of this analysis, it is reasonable to target neurophysiological states and their associated mechanisms that account for impaired human performance (see Prinzel, 2002). This review has identified a number of suboptimal neurocognitive states that are predictive of degraded performance such as: mind wandering, effort withdrawal, perseveration, inattentional blindness and deafness. These states may be conceptually mapped along orthogonal dimensions of task engagement and arousal (Figure 2). Engagement is defined as an effortful investment in the service of task/cognitive goals (Pope et al., 1995; Matthews et al., 2002; Stephens et al., 2018), whereas



arousal represents a state of physiological readiness to respond to external contingencies (Pribram and McGuinness, 1975).

### The Transactional Dimensions of Engagement and Arousal

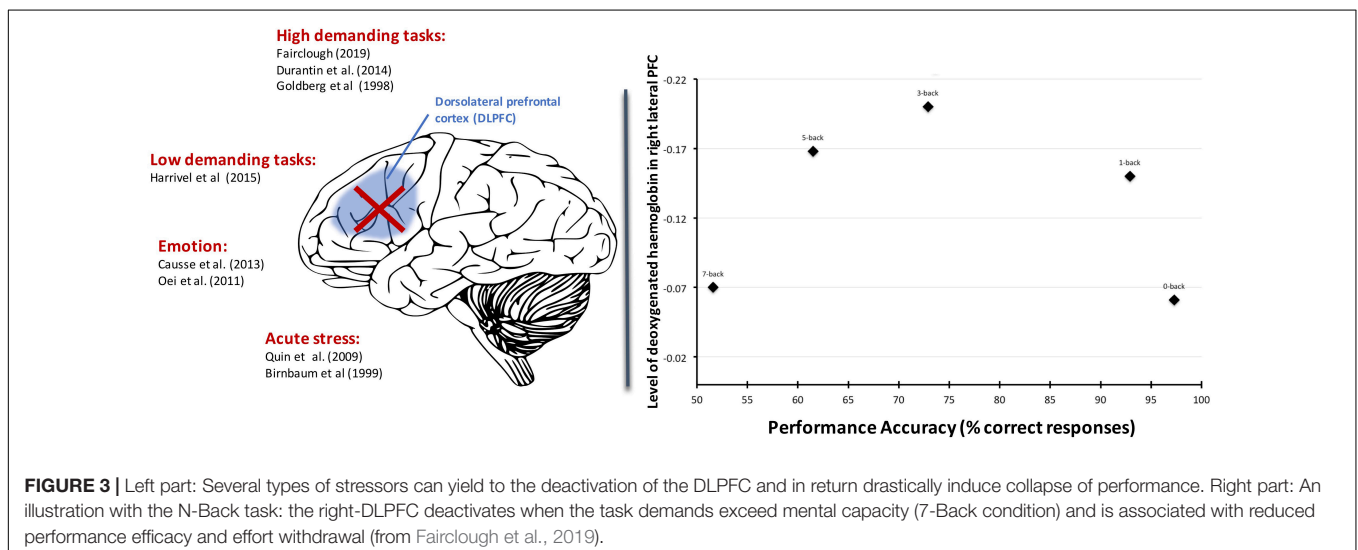
The rationale for considering the dimension of task engagement is that performance is driven by goals and motivation (Bedny and Karwowski, 2004; Fairclough et al., 2013; Leontiev, 2014). Goal-oriented cognition theorists argue for the existence of

mechanisms dedicated to maintain engagement (Atkinson and Cartwright, 1964), which are associated with an activation of an executive (Baddeley and Hitch, 1974) or task-positive network (Harrivel et al., 2013) within which the dorsolateral prefrontal cortex (DLPFC) exerts a crucial role (Goldman-Rakic, 1987; Curtis and D'Esposito, 2003). This structure plays a key role in the maintenance and updating of information that is relevant for ongoing task performance. The same structure interacts with dorsal and ventral attentional pathways to shift and focus attention to the most relevant stream of task-related information (Johnson and Zatorre, 2006). It is argued that human performance can be assessed in the context of a continuum of task engagement, ranging from disengagement (effort withdrawal, mind wandering) to high-engagement (perseveration, inattentional phenomena Lee, 2014).

Arousal makes an important contribution to the conceptual space illustrated in **Figure 2** because it modulates the homeostasis of the executive (see Arnsten, 2009 for a review) and attentional networks (see Coull, 1998 and Aston-Jones and Cohen, 2005 for review) via the dopaminergic and noradrenergic pathways. For instance, both extremes of low (Harrivel et al., 2013; Durantin et al., 2015) and high arousal can disengage the DLPFC (Goldberg et al., 1998; Arnsten, 2009; Qin et al., 2009; Causse et al., 2013; Durantin et al., 2014; Fairclough et al., 2019) and impair performance (see **Figure 3** for summary). Similarly, low (Dehais et al., 2018) and high levels of arousal (Hancock and Warm, 1989; Tracy et al., 2000; Pecher et al., 2011) can alter the interactions between the dorsal and ventral attentional networks and indistinctly that lead either to inattentional phenomena (Molloy et al., 2015; Todd et al., 2005) or effort withdrawal (Oei et al., 2012; Dehais et al., 2015).

### Monitoring Performance Through Degraded Mental States

**Table 1** presents a mapping between extremes of high and low engagement and arousal, their related neurocognitive states and how these states may be operationalized using neurophysiological



measures in the laboratory and the field. Monitoring the activation and deactivation of the DLPFC represents a promising generic avenue to predict impaired performance across diverse states such as: mind wandering (Christoff et al., 2009; Harrivel et al., 2013), effort withdrawal (Ayaz et al., 2007; Izzetoglu et al., 2007; Durantin et al., 2014; Modi et al., 2018; Fairclough et al., 2018, 2019) and perseveration (Dehais et al., 2019). However, other neurological networks and sites should be considered as part of this analysis. Mind wandering is characterized by the concomitant activation of the default network, which includes the median prefrontal cortex (Christoff et al., 2009; Harrivel et al., 2013) and areas of the parietal cortex (Christoff et al., 2009).

Secondly, attentional states, such as inattentive deafness and blindness, result from the activation of an attentional network involving the inferior frontal gyrus, the insula and the superior medial frontal cortex (Tomblu et al., 2011; Callan et al., 2018; Dehais et al., 2019). These regions represent potential candidates upon which to identify attentional failures that can be complemented by monitoring dedicated primary perceptual (see Hutchinson, 2019, for a review) and integrative cortices (Molloy et al., 2015), as well as performing connectivity analyses (Callan et al., 2018). In addition, inattentive phenomena may result from the suppression of activity in the right temporo-parietal junction (TPJ), a part of the ventral network, which also blocks reorientation of attention and the processing of unexpected stimuli (Marois et al., 2004; Todd et al., 2005).

Thirdly, measures of arousal are used to characterize high engagement and delineate distinct mental states within the category of low task engagement (Figure 2). Heart rate (HR) and heart rate variability (HRV) can be used to assess the activation or co-activation of the two branches of the autonomous nervous system (i.e., sympathetic or parasympathetic) (Fairclough, 2008; Qin et al., 2009; Kreibig, 2010). For instance, fluctuations in HR are commonly observed during high task engagement and high arousal (De Rivecourt et al., 2008; Qin et al., 2009; Dehais et al., 2011). Moreover, spectral analyses computed over the EEG signal revealed that shifts in parietal alpha [8–12] Hz and frontal theta [4–8] Hz are relevant markers of arousal (see Borghini et al., 2014, for a review, Senoussi et al., 2017).

Finally, behavioral metrics such as ocular behavior can complement the detection of low and high levels of engagement (Table 1). Hence, eye tracking metrics (e.g., fixation and dwell times, saccadic activity, blink rate) can be used to characterize mind wandering (He et al., 2011; Pepin et al., 2016), inattentive blindness (Thomas and Wickens, 2004; Wickens, 2005), perseveration (Régis et al., 2014), focal vs. diffused attention (Goldberg and Kotval, 1999; Régis et al., 2012; Dehais et al., 2015), and to characterize the level of attentional engagement in a visual task (Cowen et al., 2002; Tsai et al., 2007).

These metrics provide some relevant prospects to identify the targeted deleterious mental states for especially for field studies as long as portable devices are concerned. It is worth noting that the extraction of several features (e.g., time and frequency domains) and the use of several devices is a way for robust diagnosis. Moreover, contextual information (e.g., time of the day, time on task) should be considered as well as actions on the user interface and system parameters (e.g.,

flight parameters) if available so as to better quantify the user's mental state.

## SOLUTIONS TO MITIGATE DEGRADED PERFORMANCE

This review has identified some undesired mental states that account for degraded performance (see section “Understanding Performance Related Mental States” and “Solutions to Mitigate Degraded Performance”). A crucial step is to design cognitive countermeasures to prevent the occurrence of these phenomena. The formal framework that we proposed (see Table 1) paves the way to design neuro-adaptive technology for augmented cognition and enhanced human-machine teaming (Peysakhovich et al., 2018; Krol et al., 2019; Stamp et al., 2019). The implementation of such neuro-adaptive technology relies on a pipeline that consists of a signal acquisition step, a preprocessing step to improve the signal-to-noise ratio, a feature extraction step, a classification step to diagnose the current mental states, and lastly an adaptation step (Zander and Kothe, 2011; Roy and Frey, 2016). This last step implies the implementation of formal decisional unit (Gateau et al., 2018) that dynamically close the loop by triggering the most appropriate cognitive countermeasures (May and Baldwin, 2009). There are currently three types of mitigating solutions to instigate a change in behaviors via: (1) adaptation of the user interface, (2) adaptation of the task and of the level automation, and the (3) “neuro-adaptation” of the end-users.

### Adaptation of the User Interface

The first category of neuroadaptive countermeasure consists of triggering new types of notifications via the user interface to alert of impending hazards. The design of these countermeasures is generally grounded on neuroergonomics basis so that these warning can reach awareness when other means have failed. Following this perspective, Dehais et al. (2010, 2012), Imbert et al. (2014) and Saint Lot et al. (2020) have demonstrated that very brief (~200 ms) and located information removal was an efficient mean to mitigate perseveration by forcing disengagement from non-relevant tasks. Souza et al. (2016) demonstrated that digital nudging (see Weinmann et al., 2016) could be used to mitigate poor decision making and cognitive bias associated with perseveration. Imbert et al. (2014) designed attention-grabbing stimuli grounded on vision research and demonstrated that yellow chevrons pulsing at a cycle of 1 Hz can re-orientate attention and mitigate inattentive blindness. Jahanpour et al. (2018) has explored the design of pop-up videos that display the gestures to be performed by exploiting the property of mirror neurons. This visual “motor cue” approach was tested and drastically reduced reaction time to alerts during complex situations and appears to be a promising method to prevent effort withdrawal (Causse et al., 2012). In a similar fashion, Navarro et al. (2010) implemented a force-feedback steering wheel to prime the motor response from the driver. This device was found to optimize drivers' behavior during demanding driving scenario. This latter study demonstrated



**TABLE 1** | Psycho-physiological and behavioral markers of different mental states related to engagement.

	Disengagement		Over-Engagement		
	Mind wandering	Effort withdrawal	Perseveration	Inattentional blindness	Inattentional deafness
<b>Brain activity</b>					
MEG				↘ N400 (area V3) (Scholte et al., 2006)	↘ N100 in STG and STS (Molloy et al., 2015)
fMRI	↗ MPFC and PCC (Mason et al., 2007; Christoff et al., 2009; Fox et al., 2015) ↗ PTPC (Christoff et al., 2009) ↗ dorsal ACC and DLPFC (Christoff et al., 2009) ↗ RPF, DACC, insula, TPC, SSC & LG (Fox et al., 2015) ↗ MTL (Fox et al., 2015)	↘ DLPFC (Birnbaum et al., 1999; Qin et al., 2009), ↗ IFG and amygdala (Oei et al., 2012)	↘ DLPFC (Nagahama et al., 2005; Causse et al., 2013) ↘ ACC (Lie et al., 2006; Causse et al., 2013) ↘ bilateral temporo-parietal junction (Lie et al., 2006)	↘ fronto-parietal network (including DLPFC) (Beck et al., 2001; Pessoa and Ungerleider, 2004) temporo-parietal junction (Marois et al., 2004; Todd et al., 2005) ↗ activation of DMN (Weissman et al., 2006)	↗ IFG and SMFC, ↘ IFG-STG connectivity (Durantin et al., 2017)
fNIRS	↗ MPFC (Harrivel et al., 2013; Durantin et al., 2015) ↘ DLPFC (Harrivel et al., 2013)	↘ DLPFC (Durantin et al., 2014; Fairclough et al., 2019)	↘ Left PFC (Kalia et al., 2018)	↘ occipital lobe (Kojima and Suzuki, 2010)	
EEG	↗ $\alpha$ power over occipital sites (Gouraud et al., 2018) ↘ ( $\alpha$ and $\beta$ power (auditory stimuli) (Braboszcz and Delorme, 2011) ↗ ( $\theta$ power (auditory stimuli) (Braboszcz and Delorme, 2011) ↘ N1 (Kam et al., 2011) ↘ N4 (O'Connell et al., 2009) ↘ P1 (Kam et al., 2011) ↗ P2 (Braboszcz and Delorme, 2011) ↘ P3 (Schooler et al., 2011)	↘ frontal $\theta$ power (Gärtner et al., 2014) ↘ P3 (Dierolf et al., 2017) ↘ frontal ( $\theta$ power and $\alpha$ power (Ewing et al., 2016; Fairclough and Ewing, 2017)	↘ Event Related Coherence between midfrontal and right-frontal electrodes (Carrillo-De-La-Pena and García-Larrea, 2007)	↗ ( $\alpha$ band power (Mathewson et al., 2009) ↘ P1 (Pourtois et al., 2006; Mathewson et al., 2009) ↘ P2 (Mathewson et al., 2009) ↗ N170 (Pourtois et al., 2006) ↘ P3 (Pourtois et al., 2006; Mathewson et al., 2009)	↘ N1 (Callan et al., 2018; Dehais et al., 2019a,b) ↘ P3 (Puschmann et al., 2013; Scannella et al., 2013; Giraudet et al., 2015b; Dehais et al., 2019a,b) ↘ ( $\alpha$ power in IFG (Dehais et al., 2019a) ↘ phase synchrony in ( $\alpha$ and $\theta$ frequencies (Callan et al., 2018) ↗ engagement ratio (Dehais et al., 2017)
<b>ANS activity</b>					
ECG	↗ heart rate variability (Smith, 1981) ↗ heart rate (Smith, 1981)	↘ minimum LF/HF ratio (Durantin et al., 2014) ↘ minimum pre-ejection period (Mallat et al., 2019)	↗ heart rate (Dehais et al., 2011)		↗ heart rate (Dehais et al., 2014)
Skin conductance	↘ skin conductance (Smith, 1981)				
<b>Ocular activity</b>					
Eye-tracking	↗ number of blinks (Uzzaman and Joordens, 2011) ↘ pupil diameter (Grandchamp et al., 2014) ↗ gaze fixity (He et al., 2011; Pepin et al., 2016)	↗ maximum pupil diameter (Peavler, 1974) ↗ explore/exploit ratio (Dehais et al., 2015)	↘ switching rate between areas of interest (Régis et al., 2014) ↗ fixation duration on irrelevant areas of interest (Régis et al., 2014)	↘ saccades ↗ fixation duration (Cowen et al., 2002; Tsai et al., 2007; Régis et al., 2012) ↘ fixated areas of interest (Thomas and Wickens, 2004)	↘ pupil diameter (Causse et al., 2016)

The blue and pink color-code respectively tags states induced by low and high task demand. RIFG, right inferior frontal gyrus; DMN, default mode network, MFG, middle frontal gyrus; ACC, anterior cingulate cortex; LFC, lateral frontal cortex; STC, superior temporal cortex; PFC, prefrontal cortex; PCC, posterior cingulate cortex; MPFC, medial prefrontal cortex; PTPC, posterior temporoparietal cortex; DLPFC, dorsolateral prefrontal cortex; RPF, rostralateral prefrontal cortex; DACC, dorsal anterior cingulate cortex; TPC, temporo-parietal cortex; SSC, secondary somatosensory cortex; LG, lingual gyrus; MTL, medial temporal lobe; SMFC, superior medial frontal cortex; IFG, inferior frontal gyrus; STS, superior temporal sulcus, STG, superior temporal gyrus.

how tactile notifications can alert human operators of impending hazards (Lewis et al., 2014; Russell et al., 2016), especially when other sensory channels of information (e.g., visual stream) are

saturated (Elliott et al., 2011). However, there are potential limits to the effectiveness of these types of notifications and stimulation (Murphy and Dalton, 2016; Riggs and Sarter, 2019).

Other research indicates that multimodal alerts (Giraudet et al., 2015a; Gaspar et al., 2017) increase the likelihood of attentional capture. In addition, Lee et al. (2018) designed a motion seat that modifies the driver's seat position and posture across time to diminish the potential deleterious effect of mind wandering. Similar concepts have been applied to aviation (Zaneboni and Saint-Jalmes, 2016).

## Task and Automation Adaptation

The second category of neuroadaptive countermeasure is the dynamic reallocation of tasks between humans and automation to maintain the performance efficacy of the operators (Freeman et al., 1999; Parasuraman et al., 1999; Prinzel et al., 2000; Scerbo, 2008; Stephens et al., 2018). The underlying concept in this case is to optimize human-human or human(s)-system(s) cooperation according to criteria of availability and skills of human and artificial agents (Gateau et al., 2016). For instance, Prinzel et al. (2000) utilized the continuous monitoring of brain waves that could be used to drive the level of automation and optimize the user's level of task engagement. Similarly, some authors managed to optimize air traffic controllers' task demand by triggering different levels of assistance (Aricò et al., 2016; Di Flumeri et al., 2019). These latter studies reported better human performance when neuro-adaptive automation was switched on compared to other conditions. Gateau et al. (2016) implemented an online attentional state estimator coupled with a stochastic decision framework to dynamically adapt authority sharing between human and robots in a search and rescue scenario to prevent effort withdrawal on the part of the human. In a more extreme fashion, Callan et al. (2016) revealed that it is possible to decode user motor intention so automation can perform on behalf of the user to drastically reduce the response time in emergency situations (e.g., collision with terrain). In the future, it is assumed that aircraft designers will implement adaptive automation technology that takes over from the pilots by either inhibiting their inputs on the flight deck or performing automated evasive actions (e.g., automatic pull-up) to prevent from perseveration. A complementary approach is to modulate task difficulty to maintain the task challenging but achievable while preventing the occurrence of task withdrawal (Ewing et al., 2016) or mind wandering (Freeman et al., 2004; Ewing et al., 2016). The online modulation of the tasks does not necessarily reduce the difficulty of the task. For instance, Verwey and colleagues demonstrated that the addition of an entertaining task while driving improved the operator's ability to maintain their level of task engagement over long period of time (Verwey and Zaidel, 1999). Similarly, it has been suggested that switching the types of tasks presented to the user can prevent the deleterious effect of fatigue and disengagement (Hockey, 2011).

## Neuro-Adaptation of the End-User(s)

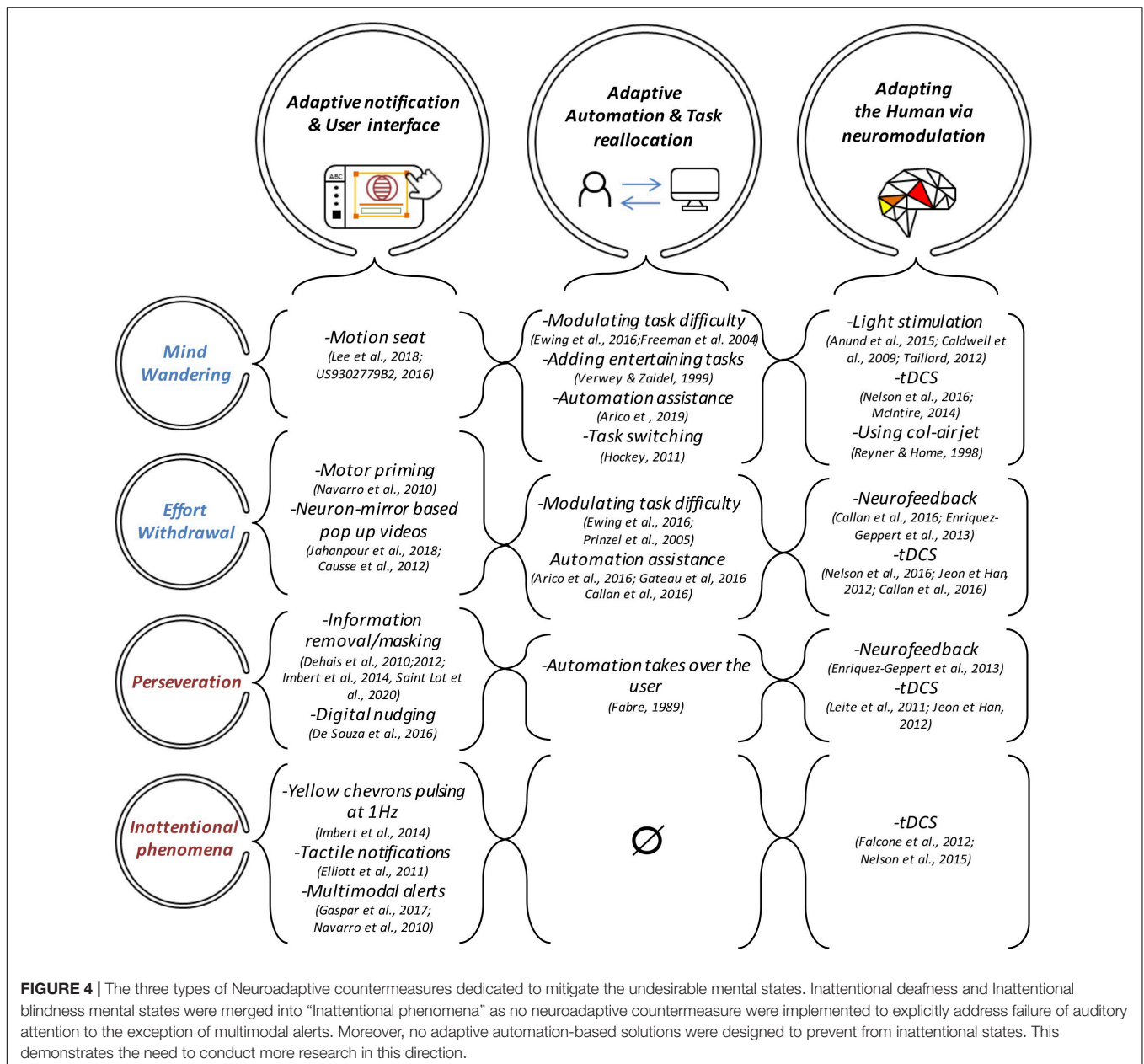
The third and final category aims to warn the users of their mental state and "stimulate" neurological activity in order to augment performance. One of the most promising approach relies on the implementation of Neurofeedback (see Gruzelier, 2014; Enriquez-Geppert et al., 2017 for reviews). The principle

of the latter technique is to provide feedback in real-time to the users of their mental states in the form of a visual, tactile or auditory stimulus. The users can utilize these signals learn to regulate their brain activity and in return improve their executive (Enriquez-Geppert et al., 2013), mental flexibility (Enriquez-Geppert et al., 2014), and attentional abilities (Egner and Gruzelier, 2001) as well as enhance their task engagement (Egner and Gruzelier, 2004). However, the effects of this approach on mind wandering remain unclear (Gonçalves et al., 2018). Transcranial direct current stimulation (tDCS) represents a technique of neuromodulation that can be used to boost executive functioning (see Callan and Perrey, 2019; Cinel et al., 2019). This portable device can be combined with EEG and fNIRS and used in the context of real-life task performance for the purpose of on-line neuromodulation (McKendrick et al., 2015; Gateau et al., 2018). For example, a number of studies support the position that neurostimulation can: enhance mental flexibility and mitigate perseveration (Leite et al., 2011; Jeon and Han, 2012), improve visual attention (Falcone et al., 2012; Nelson et al., 2015), improve executive functioning in multitasking situations (Nelson et al., 2016) and increase alertness (McIntire et al., 2014; Nelson et al., 2014). There are other types of environmental stimulation such as vivid light exposure, especially during night flights, which can promote an optimal level of alertness (see Anund et al., 2015) without altering flight crew performance (see Caldwell et al., 2009). Promising results have also been highlighted by using light exposure in cars (Taillard et al., 2012). The use of light exposure and tDCS should be considered with caution as there is a need to investigate the very long-term efficiency and potential side effects. Alternatively, some authors proposed to use cold-air jet to decrease hypovigilance (Reyner and Horne, 1998), but with contradictory findings.

## Synthesis of Neuro-Adaptive Solutions

The following illustration (see **Figure 4**) depicts the three families of neuro-adaptive based solutions to mitigate performance impairment.

The three types of neuroadaptive solutions offer promising prospects to mitigate the onset and likelihood of undesirable neurocognitive states. However, they should be delivered in a transparent, meaningful, and timely manner (i.e., when needed) so they are relevant and understood (Dorneich et al., 2016; Sebok et al., 2017), otherwise these types of intervention have the potential for undesirable consequences, such as performance impairment and reduced trust in technology; this point is particularly true for adaptive automation solutions that take over from humans, especially under critical scenarios (see Dorneich et al., 2016; Dehais et al., 2019). One solution is to combine different families of neuroadaptive cognitive countermeasures to maximize their efficiency. Ideally, we would argue to use a gradient of solutions such as (1) the continuous display of the users' mental states via neurofeedback techniques to give them the opportunity to regulate their brain activity; (2) using notifications to suggest to the users to delegate some tasks to automation in case they don't manage to modulate their mental states; (3) adapting the user interface (e.g., information



removal, flashing yellow chevrons) in case of a critical situation is detected and the previous solutions were inefficient; and (4) taking over if the users do not respond to any of the previous countermeasures.

## CONCLUSION

This paper has argued that the concept of a limited resource provides a limited explanation for the breakdown of operational performance. Our neurophysiological analysis describes a number of additional mechanisms, such as perseveration and effort withdrawal, which do not represent finite resources *per se*. In both cases, explanations for performance breakdown

are based upon neurological processes, such as dominance of specific neural networks or the heightened activity of specific mechanisms. We propose a two-dimensional framework of engagement and arousal that captures the importance of specific degraded mental states associated with poor performance. The rationale for including the transactional concept of engagement in this scheme is to account for the goal-oriented aspect of cognition. The benefit of including the transactional concept of arousal is to make a distinction between two categories of disengagement, one that is accompanied by high arousal (effort withdrawal) and low arousal (mind wandering) – and to link this conceptual distinction to known neurophysiological effects (see **Figure 1**). Nonetheless, this approach remains at the conceptual level and minimizes connections to the complexity of brain

functioning. To that end, we reviewed and identified several markers at the neurophysiological, physiological and behavioral level of undesirable mental states linked to poor performance.

This neuroergonomic framework encompasses operationalizations of these undesirable states that can be monitored continuously in an objective fashion. Such considerations eventually lead to propose a typology of neuroadaptive countermeasures and open promising perspectives to mitigate the degradation of human performance. However, to the authors' very best knowledge, most of the neuroadaptive experimental studies have focused on human-machine dyad situations. We believe that recent research on hyperscanning (Babiloni and Astolfi, 2014), physiological synchrony (Palumbo et al., 2017) and collaborative BCIs (Cinel et al., 2019) have opened promising prospects to improve teaming such as human-human, human(s)-machine(s) interactions. Future research should involve more complex teaming scenarios and enrich the different neuroadaptive solutions.

## REFERENCES

- Andrews-Hanna, J. R., Smallwood, J., and Spreng, R. N. (2014). The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Ann. N. Y. Acad. Sci.* 1316:29. doi: 10.1111/nyas.12360
- Annett, J. (2002). Subjective rating scales: science or art? *Ergonomics* 45, 966–987. doi: 10.1080/00140130210166951
- Anund, A., Fors, C., Kecklund, G., Leeuwen, W. V., and Åkerstedt, T. (2015). *Countermeasures for Fatigue in Transportation: A Review of Existing Methods for Drivers on Road, Rail, Sea And In Aviation*. Linköping: Statens väg- och transportforskningsinstitut.
- Aricò, P., Borghini, G., Di Flumeri, G., Colosimo, A., Bonelli, S., Golfetti, A., et al. (2016). Adaptive automation triggered by EEG-based mental workload index: a passive brain-computer interface application in realistic air traffic control environment. *Front. Hum. Neurosci.* 10:539. doi: 10.3389/fnhum.2016.00539
- Arnsten, A. F. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nat. Rev. Neurosci.* 10:410. doi: 10.1038/nrn2648
- Arnsten, A. F., Wang, M. J., and Paspalas, C. D. (2012). Neuromodulation of thought: flexibilities and vulnerabilities in prefrontal cortical network synapses. *Neuron* 76, 223–239. doi: 10.1016/j.neuron.2012.08.038
- Aston-Jones, G., and Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. *Annu. Rev. Neurosci.* 28, 403–450. doi: 10.1146/annurev.neuro.28.061604.135709
- Atkinson, J. W., and Cartwright, D. (1964). Some neglected variables in contemporary conceptions of decision and performance. *Psychol. Rep.* 14, 575–590. doi: 10.2466/pr0.1964.14.2.575
- Ayaz, H., and Dehais, F. (eds) (2018). *Neuroergonomics: The Brain at Work and in Everyday Life*. Cambridge, MA: Academic Press.
- Ayaz, H., Izzetoglu, M., Bunce, S., Heiman-Patterson, T., and Onaral, B. (2007). "Detecting cognitive activity related hemodynamic signal for brain computer interface using functional near infrared spectroscopy," in *Proceedings of the 3rd International IEEE EMBS conference: CNE'07*, Hawaii, 342–345.
- Ayaz, H., Shewokis, P. A., Bunce, S., Izzetoglu, K., Willems, B., and Onaral, B. (2012). Optical brain monitoring for operator training and mental workload assessment. *Neuroimage* 59, 36–47. doi: 10.1016/j.neuroimage.2011.06.023
- Babiloni, F., and Astolfi, L. (2014). Social neuroscience and hyperscanning techniques: past, present and future. *Neurosci. Biobehav. Rev.* 44, 76–93. doi: 10.1016/j.neubiorev.2012.07.006
- Baddeley, A. D., and Hitch, G. (1974). "Working memory," in *The Psychology of Learning and Motivation: Advances in Research and Theory*, Vol. 8, eds G. H. Bower (New York, NY: Academic Press), 47–89. doi: 10.1016/S0079-7421(08)60452-1
- Beanland, V., and Chan, E. H. C. (2016). The relationship between sustained inattention blindness and working memory capacity. *Attent. Percept. Psychophys.* 78, 808–817. doi: 10.3758/s13414-015-1027-x
- Beatty, J. (1986). "Computation, control and energetics: a biological perspective," in *Energetics and Human Information Processing*, ed. G. R. J. Hockey (Dordrecht: Springer).
- Beck, D. M., Rees, G., Frith, C. D., and et Lavie, N. (2001). Neural correlates of change detection and change blindness. *Nat. Neurosci.* 4, 645–650. doi: 10.1038/88477
- Bedny, G. Z., and Karwowski, W. (2004). Activity theory as a basis for the study of work. *Ergonomics* 47, 134–153. doi: 10.1080/00140130310001617921
- Birnbaum, S., Gobeske, K. T., Auerbach, J., Taylor, J. R., and Arnsten, A. F. (1999). A role for norepinephrine in stress-induced cognitive deficits:  $\alpha$ -1-adrenoceptor mediation in the prefrontal cortex. *Biol. Psychiatry* 46, 1266–1274. doi: 10.1016/s0006-3223(99)00138-9
- Borghini, G., Astolfi, L., Vecchiato, G., Mattia, D., and Babiloni, F. (2014). Measuring neurophysiological signals in aircraft pilots and car drivers for the assessment of mental work- load, fatigue and drowsiness. *Neurosci. Biobehav. Rev.* 44, 58–75. doi: 10.1016/j.neubiorev.2012.10.003
- Borragan Pedraz, G., and Peigneux, P. (2016). *Behavioural Bases and Functional Dynamics of Cognitive Fatigue*, Doctorat. Sciences psychologiques et de l'éducation, Louvain.
- Braboszcz, C., and Delorme, A. (2011). Lost in thoughts: neural markers of low alertness during mind wandering. *Neuroimage* 54, 3040–3047. doi: 10.1016/j.neuroimage.2010.10.008
- Brand-D'Abrescia, M., and Lavie, N. (2008). Task coordination between and within sensory modalities: effects on distraction. *Percept. Psychophys.* 70, 508–515. doi: 10.3758/pp.70.3.508
- Bredemeier, K., and Simons, D. J. (2012). Working memory and inattention blindness. *Psychon. Bull. Rev.* 19, 239–244. doi: 10.3758/s13423-011-0204-8
- Broadbent, D. E. (1971). *Decision and Stress*. Oxford: Academic Press.
- Bromiley, M. (2008). Have you ever made a mistake? *RCoA Bull.* 48, 2442–2445.
- Brynjolfsson, E., and McAfee, A. (2014). *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, 1st Edn. New York, NY: W. W. Norton & Company.
- Caldwell, J. A., Mallis, M. M., Caldwell, J. L., Paul, M. A., Miller, J. C., and Neri, D. F. (2009). Fatigue countermeasures in aviation. *Aviat. Space Environ. Med.* 80, 29–59. doi: 10.3357/asem.2435.2009
- Callan, D., and Perrey, S. (2019). "The use of tDCS and rTMS methods in neuroergonomics," in *Neuroergonomics*, eds H. Ayaz and F. Dehais (Cambridge, MA: Academic Press), 31–33. doi: 10.1016/b978-0-12-811926-6.00005-1
- Callan, D. E., Gateau, T., Durantin, G., Gonthier, N., and De-Hais, F. (2018). Disruption in neural phase synchrony is related to identification of inattentional



- deafness in real-world setting. *Hum. Brain Mapp.* 39, 2596–2608. doi: 10.1002/hbm.24026
- Callan, D. E., Terzibas, C., Cassel, D. B., Sato, M. A., and Parasuraman, R. (2016). The brain is faster than the hand in split-second intentions to respond to an impending hazard: a simulation of neuroadaptive automation to speed recovery to perturbation in flight attitude. *Front. Hum. Neurosci.* 10:187. doi: 10.3389/fnhum.2016.00187
- Carrillo-De-La-Pena, M. T., and García-Larrea, L. (2007). Right frontal event related EEG coherence (ERCoh) differentiates good from bad performers of the Wisconsin Card Sorting Test (WCST). *Clin. Neurophysiol.* 37, 63–75. doi: 10.1016/j.neucli.2007.02.002
- Carver, C. S., and Scheier, M. F. (2000). “On the structure of behavioural self-regulation,” in *Handbook of Self-Regulation*, eds M. Boekaerts, P. R. Pintrich, and M. Zeidner (San Diego, CA: Academic Press), 41–84. doi: 10.1016/b978-012109890-2/50032-9
- Causse, M., Imbert, J. P., Giraudet, L., Jouffrais, C., and Tremblay, S. (2016). The role of cognitive and perceptual loads in inattentive deafness. *Front. Hum. Neurosci.* 10:344. doi: 10.3389/fnhum.2016.00344
- Causse, M., Péran, P., Dehais, F., Caravasso, C. F., Zeffiro, T., Sabatini, U., et al. (2013). Affective decision making under uncertainty during a plausible aviation task: an fMRI study. *NeuroImage* 71, 19–29. doi: 10.1016/j.neuroimage.2012.12.060
- Causse, M., Phan, J., Ségonzac, T., and Dehais, F. (2012). Mirror neuron based alerts for control flight into terrain avoidance. *Adv. Cognit. Eng. Neuroergon.* 16, 157–166.
- Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., and Schooler, J. W. (2009). Experience sampling during fmri reveals default network and executive system contributions to mind wandering. *Proc. Natl. Acad. Sci. U.S.A.* 106, 8719–8724. doi: 10.1073/pnas.0900234106
- Chrousos, G. P. (2009). Stress and disorders of the stress system. *Nat. Rev. Endocrinol.* 5:374. doi: 10.1038/nrendo.2009.106
- Cinell, C., Valeriani, D., and Poli, R. (2019). Neurotechnologies for human cognitive augmentation: current state of the art and future prospects. *Front. Hum. Neurosci.* 13:13. doi: 10.3389/fnhum.2019.00013
- Colflesh, G. J., and Conway, A. R. (2007). Individual differences in working memory capacity and divided attention in dichotic listening. *Psychon. Bull. Rev.* 14, 699–703. doi: 10.3758/bf03196824
- Corbetta, M., Patel, G., and Shulman, G. L. (2008). The reorienting system of the human brain: from environment to theory of mind. *Neuron* 58, 306–324. doi: 10.1016/j.neuron.2008.04.017
- Corbetta, M., and Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nat. Rev. Neurosci.* 3:201. doi: 10.1038/nrn755
- Coull, J. T. (1998). Neural correlates of attention and arousal: insights from electrophysiology, functional neuroimaging and psychopharmacology. *Prog. Neurobiol.* 55, 343–361. doi: 10.1016/s0301-0082(98)00011-2
- Coultrip, R., Granger, R., and Lynch, G. (1992). A cortical model of winner-take-all competition via lateral inhibition. *Neural Netw.* 5, 47–54. doi: 10.1016/s0893-6080(05)80006-1
- Cowen, L., Ball, L. J., and Delin, J. (2002). “An eye movement analysis of web page usability,” in *People and Computers Xvi-memorable Yet Invisible*, eds X. Faulkner, J. Finlay, and F. Détéienne (Berlin: Springer), 317–335. doi: 10.1007/978-1-4471-0105-5\_19
- Curtis, C. E., and D’Esposito, M. (2003). Persistent activity in the prefrontal cortex during working memory. *Trends Cognit. Sci.* 7, 415–423. doi: 10.1016/s1364-6613(03)00197-9
- De Rivecourt, M., Kuperus, M. N., Post, W. J., and Mulder, L. J. M. (2008). Cardiovascular and eye activity measures as indices for momentary changes in mental effort during simulated flight. *Ergonomics* 51, 1295–1319. doi: 10.1080/00140130802120267
- De Waard, D. (1996). *The Measurement of Driver Mental Workload*, PhD Thesis., Groningen: Rijksuniversiteit Groningen.
- Dehais, F., Causse, M., and Tremblay, S. (2011). Mitigation of conflicts with automation: use of cognitive countermeasures. *Hum. Fact.* 53, 448–460. doi: 10.1177/0018720811418635
- Dehais, F., Causse, M., Vachon, F., Régis, N., Menant, E., and Tremblay, S. (2014). Failure to detect critical auditory alerts in the cockpit: evidence for inattentive deafness. *Hum. Fact.* 56, 631–644. doi: 10.1177/0018720813510735
- Dehais, F., Causse, M., Vachon, F., and Tremblay, S. (2012). Cognitive conflict in human-automation interactions: a psychophysiological study. *Appl. Ergon.* 43, 588–595. doi: 10.1016/j.apergo.2011.09.004
- Dehais, F., Duprès, A., Di Flumeri, G., Verdière, K. J., Borghini, G., Babiloni, F., et al. (2018). *Monitoring Pilots Cognitive Fatigue with Engagement Features in Simulated and actual Flight Conditions Using an Hybrid fNIRS-EEG Passive BCI.* IEEE SMC. Available at: <https://hal.archives-ouvertes.fr/hal-01959452>.
- Dehais, F., Hodgetts, H. M., Causse, M., Behrend, J., Durantin, G., and Tremblay, S. (2019). Momentary lapse of control: a cognitive continuum approach to understanding and mitigating perseveration in human error. *Neurosci. Biobehav. Rev.* 100, 252–262. doi: 10.1016/j.neubiorev.2019.03.006
- Dehais, F., Peysakhovich, V., Scannella, S., Fongue, J., and Gateau, T. (2015). “Automation surprise in aviation: real-time solutions,” in *Proceedings of the 33rd annual ACM conference on human factors in computing systems*, New York, NY, 2525–2534.
- Dehais, F., Rida, I., Roy, R., Iversen, J., Mullen, T., and Callan, D. (2019a). “A pBCI to predict attentional error before it happens in real flight conditions,” in *Proceedings of the Conference: 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, Bari.
- Dehais, F., Roy, R. N., and Scannella, S. (2019b). Inattentive deafness to auditory alarms: inter-individual differences, electrophysiological signature and single trial classification. *Behav. Brain Res.* 360, 51–59. doi: 10.1016/j.bbr.2018.11.045
- Dehais, F., Roy, R. N., Durantin, G., Gateau, T., and Callan, D. (2017). “EEG-engagement index and auditory alarm misperception: an inattentive deafness study in actual flight condition,” in *Proceedings of the International Conference on Applied Human Factors and Ergonomics*, Washington D.C., 227–234. doi: 10.1007/978-3-319-60642-2\_21
- Dehais, F., Tessier, C., Christophe, L., and Reuzeau, F. (2010). “The perseveration syndrome in the pilots’ activity: guide-lines and cognitive countermeasures,” in *Human Error, Safety and Systems Development*, eds P. Palanque, J. Vanderdonck, and M. Winkler (Berlin: Springer), 68–80. doi: 10.1007/978-3-642-11750-3\_6
- Di Flumeri, G., De Crescenzo, F., Berberian, B., Ohneiser, O., Kramer, J., Aricò, P., et al. (2019). Brain-computer interface-based adaptive automation to prevent out-of-the-loop phenomenon in air traffic controllers dealing with highly automated systems. *Front. Hum. Neurosci.* 13:296. doi: 10.3389/fnhum.2019.00296
- Dierolf, A. M., Fechtner, J., Böhnke, R., Wolf, O. T., and Naumann, E. (2017). Influence of acute stress on response inhibition in healthy men: an ERP study. *Psychophysiology* 54, 684–695. doi: 10.1111/psyp.12826
- Dolan, R. J. (2002). Emotion, cognition, and behavior. *Science* 298, 1191–1194.
- Dolcos, F., and McCarthy, G. (2006). Brain systems mediating cognitive interference by emotional distraction. *J. Neurosci.* 26, 2072–2079. doi: 10.1523/jneurosci.5042-05.2006
- Dorneich, M. C., Rogers, W., Whitlow, S. D., and DeMers, R. (2016). Human performance risks and benefits of adaptive systems on the flight deck. *Int. J. Aviat. Psychol.* 26, 15–35. doi: 10.1080/10508414.2016.1226834
- Duffy, E. (1962). *Activation and Behaviour*. New York, NY: Wiley.
- Durantini, G., Dehais, F., and Delorme, A. (2015). Characterization of mind wandering using fNIRS. *Front. Syst. Neurosci.* 9:45. doi: 10.3389/fnsys.2015.00045
- Durantini, G., Dehais, F., Gonthier, N., Terzibas, C., and Callan, D. E. (2017). Neural signature of inattentive deafness. *Hum. Brain Mapp.* 38, 5440–5455. doi: 10.1002/hbm.23735
- Durantini, G., Gagnon, J.-F., Tremblay, S., and Dehais, F. (2014). Using near infrared spectroscopy and heart rate variability to detect mental overload. *Behav. Brain Res.* 259, 16–23. doi: 10.1016/j.bbr.2013.10.042
- Edworthy, J., Reid, S., Peel, K., Lock, S., Williams, J., Newbury, C., et al. (2018). The impact of workload on the ability to localize audible alarms. *Appl. Ergon.* 72, 88–93. doi: 10.1016/j.apergo.2018.05.006
- Egner, T., and Gruzelier, J. H. (2001). Learned self-regulation of EEG frequency components affects attention and event-related brain potentials in humans. *Neuroreport* 12, 4155–4159. doi: 10.1097/00001756-200112210-00058
- Egner, T., and Gruzelier, J. H. (2004). EEG biofeedback of low beta band components: frequency-specific effects on variables of attention and event-related brain potentials. *Clin. Neurophysiol.* 115, 131–139. doi: 10.1016/s1388-2457(03)00353-5

- Ellenbogen, M. A., Schwartzman, A. E., Stewart, J., and Walker, C.-D. (2006). Automatic and effortful emotional information processing regulates different aspects of the stress response. *Psychoneuroendocrinology* 31, 373–387. doi: 10.1016/j.psyneuen.2005.09.001
- Elliott, L. R., Schmeisser, E. T., and Redden, E. S. (2011). “Development of tactile and haptic systems for US infantry navigation and communication,” in *Proceedings of the Symposium on Human Interface* (Berlin: Springer), 399–407. doi: 10.1007/978-3-642-21793-7\_45
- Enriquez-Geppert, S., Huster, R. J., Figge, C., and Herrmann, C. S. (2014). Self-regulation of frontal-midline theta facilitates memory updating and mental set shifting. *Front. Behav. Neurosci.* 8:420. doi: 10.3389/fnbeh.2014.00420
- Enriquez-Geppert, S., Huster, R. J., and Herrmann, C. S. (2013). Boosting brain functions: improving executive functions with behavioral training, neurostimulation, and neurofeedback. *Int. J. Psychophysiol.* 88, 1–16. doi: 10.1016/j.ijpsycho.2013.02.001
- Enriquez-Geppert, S., Huster, R. J., and Herrmann, C. S. (2017). EEG-neurofeedback as a tool to modulate cognition and behavior: a review tutorial. *Front. Hum. Neurosci.* 11:51. doi: 10.3389/fnhum.2017.00051
- Ewing, K. C., Fairclough, S. H., and Gilleade, K. (2016). Evaluation of an adaptive game that uses EEG measures validated during the design process as inputs to a biocybernetic loop. *Front. Hum. Neurosci.* 10:223. doi: 10.3389/fnhum.2016.00223
- Fairclough, S., Ewing, K., Burns, C., and Kreplin, U. (2019). “Neural efficiency and mental workload: locating the red line,” in *Neuroergonomics*, eds A. Johnson and R. W. Proctor (Cambridge, MA: Academic Press), 73–77. doi: 10.1016/b978-0-12-811926-6.00012-9
- Fairclough, S. H. (2008). Fundamentals of physiological computing. *Interact. Comput.* 21, 133–145. doi: 10.1016/j.intcom.2008.10.011
- Fairclough, S. H., Burns, C., and Kreplin, U. (2018). FNIRS activity in the prefrontal cortex and motivational intensity: impact of working memory load, financial reward, and correlation-based signal improvement. *Neurophotonics* 5, 1–10.
- Fairclough, S. H., and Ewing, K. (2017). The effect of task demand and incentive on neurophysiological and cardiovascular markers of effort. *Int. J. Psychophysiol.* 119, 58–66. doi: 10.1016/j.ijpsycho.2017.01.007
- Fairclough, S. H., Gilleade, K., Ewing, K. C., and Roberts, J. (2013). Capturing user engagement via psychophysiology: measures and mechanisms for biocybernetic adaptation. *Int. J. Auton. Adapt. Commun. Syst.* 6, 63–79.
- Falcone, B., Coffman, B. A., Clark, V. P., and Parasuraman, R. (2012). Transcranial direct current stimulation augments perceptual sensitivity and 24-hour retention in a complex threat detection task. *PLoS ONE* 7:e34993. doi: 10.1371/journal.pone.0034993
- Fox, K. C., Spreng, R. N., Ellamil, M., Andrews-Hanna, J. R., and Christoff, K. (2015). The wandering brain: meta-analysis of functional neuroimaging studies of mind-wandering and related spontaneous thought processes. *Neuroimage* 111, 611–621. doi: 10.1016/j.neuroimage.2015.02.039
- Freeman, F. G., Mikulka, P. J., Prinzl, L. J., and Scerbo, M. W. (1999). Evaluation of an adaptive automation system using three EEG indices with a visual tracking task. *Biol. Psychol.* 50, 61–76. doi: 10.1016/s0301-0511(99)00002-2
- Freeman, F. G., Mikulka, P. J., Scerbo, M. W., and Scott, L. (2004). An evaluation of an adaptive automation system using a cognitive vigilance task. *Biol. Psychol.* 67, 283–297. doi: 10.1016/j.biopsycho.2004.01.002
- Gärtner, M., Rohde-Liebenau, L., Grimm, S., and Bajbouj, M. (2014). Working memory-related frontal theta activity is decreased under acute stress. *Psychoneuroendocrinology* 43, 105–113. doi: 10.1016/j.psyneuen.2014.02.009
- Gaspar, J. G., Brown, T. L., Schwarz, C. W., Lee, J. D., Kang, J., and Higgins, J. S. (2017). Evaluating driver drowsiness countermeasures. *Traff. Inj. Prevent.* 18, S58–S63.
- Gateau, T., Ayaz, H., and Dehais, F. (2018). In silico versus over the clouds: on-the-fly mental state estimation of aircraft pilots, using a functional near infrared spectroscopy based passive-BCI. *Front. Hum. Neurosci.* 12:187. doi: 10.3389/fnhum.2018.00187
- Gateau, T., Chanel, C. P. C., Le, M. H., and Dehais, F. (2016). “Considering human’s non-deterministic behavior and his availability state when designing a collaborative human-robots system,” in *Proceedings of the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Las Vegas, NV, 4391–4397.
- Giraudet, L., Imbert, J. P., Bérenger, M., Tremblay, S., and Causse, M. (2015a). The Neuroergonomic evaluation of human machine interface design in air traffic control using behavioral and EEG/ERP measures. *Behav. Brain Res.* 294, 246–253. doi: 10.1016/j.bbr.2015.07.041
- Giraudet, L., St-Louis, M.-E., Scannella, S., and Causse, M. (2015b). P300 event-related potential as an indicator of intentional deafness? *PLoS ONE* 10:e0118556. doi: 10.1371/journal.pone.0118556
- Goldberg, J. H., and Kotval, X. P. (1999). Computer interface evaluation using eye movements: methods and constructs. *Int. J. Ind. Ergon.* 24, 631–645. doi: 10.1016/s0169-8141(98)00068-7
- Goldberg, T. E., Berman, K. F., Fleming, K., Ostrem, J., Van Horn, J. D., Esposito, G., et al. (1998). Uncoupling cognitive workload and prefrontal cortical physiology: a PER rCBF study. *Neuroimage* 7, 296–303. doi: 10.1006/nimg.1998.0338
- Goldman-Rakic, P. (1987). *Handbook of Physiology. The Nervous System*. Bethesda, MD: American Physiological Society, 373417.
- Gonçalves, ÓF., Carvalho, S., Mendes, A. J., Leite, J., and Boggio, P. S. (2018). Neuromodulating attention and mind-wandering processes with a single session real time EEG. *Appl. Psychophysiol. Biofeedback* 43, 143–151. doi: 10.1007/s10484-018-9394-4
- Gouraud, J., Delorme, A., and Berberian, B. (2018). Out of the loop, in your bubble: mind wandering is independent from automation reliability, but influences task engagement. *Front. Hum. Neurosci.* 12:383. doi: 10.3389/fnhum.2018.00383
- Grandchamp, R., Braboszcz, C., and Delorme, A. (2014). Oculometric variations during mind wandering. *Front. Psychol.* 5:31. doi: 10.3389/fpsyg.2014.00031
- Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. I: a review of cognitive and affective outcome in healthy participants. *Neurosci. Biobehav. Rev.* 44, 124–141. doi: 10.1016/j.neubiorev.2013.09.015
- Hancock, P. A., and Desmond, P. A. (2001). *Stress, Workload, and Fatigue*. Mahwah, NJ: Erlbaum.
- Hancock, P. A., and Meshkati, N. (1988). *Human Mental Workload*. Amsterdam: North-Holland.
- Hancock, P. A., and Warm, J. S. (1989). A dynamic model of stress and sustained attention. *Hum. Fact.* 31, 519–537. doi: 10.1177/001872088903100503
- Harrivel, A. R., Weissman, D. H., Noll, D. C., and Peltier, S. J. (2013). Monitoring attentional state with fnirs. *Front. Human Neurosci.* 7:861. doi: 10.3389/fnhum.2013.00861
- He, J., Becic, E., Lee, Y.-C., and McCarley, J. S. (2011). Mind wandering behind the wheel: performance and oculomotor correlates. *Human Factors* 53, 13–21. doi: 10.1177/0018720810391530
- Herff, C., Heger, D., Fortmann, O., Hennrich, J., Putze, F., and Schultz, T. (2014). Mental workload during n-back task—quantified in the prefrontal cortex using fNIRS. *Front. Hum. Neurosci.* 7:935. doi: 10.3389/fnhum.2013.00935
- Hockey, G. R. J. (1997). Compensatory control in the regulation of human performance under stress and high workload: a cognitive-energetical framework. *Biol. Psychol.* 45, 73–93. doi: 10.1016/s0301-0511(96)05223-4
- Hockey, G. R. J. (2011). “A motivational control theory of cognitive fatigue,” in *Cognitive Fatigue: Multidisciplinary Perspectives on Current Research and Future Applications*, ed. P. L. Ackerman (Washington, DC: American Psychological Association).
- Hockey, G. R. J., Coles, M. G., and Gaillard, A. W. (1986). “Energetical issues in research on human information processing,” in *Energetics and Human Information Processing*, eds G. M. Hockey, A. W. K. Gaillard, and M. Coles (Berlin: Springer), 3–21. doi: 10.1007/978-94-009-4448-0\_1
- Hopstaken, J. F., Van Der Linden, D., Bakker, A. B., and Kompier, M. A. (2015). A multifaceted investigation of the link between mental fatigue and task disengagement. *Psychophysiology* 52, 305–315. doi: 10.1111/psyp.12339
- Hutchinson, B. T. (2019). Toward a theory of consciousness: a review of the neural correlates of inattention blindness. *Neurosci. Biobehav. Rev.* 104, 87–99. doi: 10.1016/j.neubiorev.2019.06.003
- Imbert, J. P., Hodgetts, H. M., Parise, R., Vachon, F., Dehais, F., and Tremblay, S. (2014). Attentional costs and failures in air traffic control notifications. *Ergonomics* 57, 1817–1832. doi: 10.1080/00140139.2014.952680
- Izzetoglu, M., Bunce, S. C., Izzetoglu, K., Onaral, B., and Pour-rezaei, K. (2007). Functional brain imaging using near-infrared technology. *IEEE Eng. Med. Biol. Mag.* 26:38. doi: 10.1109/memb.2007.384094

- Jahanpour, E., Fabre, E., Dehais, F., and Causse, M. (2018). "Giving a hand to pilots with animated alarms based on mirror system functioning," in *Proceedings of the 2nd International Neuroergonomics Conference*, Philadelphia, PA.
- Jeon, S. Y., and Han, S. J. (2012). Improvement of the working memory and naming by transcranial direct current stimulation. *Ann. Rehabil. Med.* 36, 585–595.
- Johnson, J. A., and Zatorre, R. J. (2006). Neural substrates for dividing and focusing attention between simultaneous auditory and visual events. *NeuroImage* 31, 1673–1681. doi: 10.1016/j.neuroimage.2006.02.026
- Kahneman, D. (1973). *Attention and Effort*, Vol. 1063. Englewood Cliffs, NJ: Prentice-Hall.
- Kalia, V., Vishwanath, K., Knauff, K., Vellen, B. V. D., Luebke, A., and Williams, A. (2018). Acute stress attenuates cognitive flexibility in males only: an fNIRS examination. *Front. Psychol.* 9:2084. doi: 10.3389/fpsyg.2018.02084
- Kam, J. W., Dao, E., Farley, J., Fitzpatrick, K., Smallwood, J., Schooler, J. W., et al. (2011). Slow fluctuations in attentional control of sensory cortex. *J. Cognit. Neurosci.* 23, 460–470. doi: 10.1162/jocn.2010.21443
- Kobes, M., Helsloot, I., De Vries, B., and Post, J. G. (2010). Building safety and human behaviour in fire: a literature review. *Fire Saf. J.* 45, 1–11. doi: 10.1016/j.firesaf.2009.08.005
- Kojima, H., and Suzuki, T. (2010). Hemodynamic change in occipital lobe during visual search: visual attention allocation measured with NIRS. *Neuropsychologia* 48, 349–352. doi: 10.1016/j.neuropsychologia.2009.09.028
- Kramer, A., and Spinks, J. (1991). "Capacity views of human information processing," in *Handbook of Cognitive Psychophysiology: Central and Nervous Systems Approaches*, eds J. R. Jennings and M. G. H. Coles (New York: Wiley), 179–249.
- Kreibitz, S. D. (2010). Autonomic nervous system activity in emotion: a review. *Biol. Psychol.* 84, 394–421. doi: 10.1016/j.biopsycho.2010.03.010
- Kreitz, C., Furley, P., Memmert, D., and Simons, D. J. (2016a). The influence of attention set, working memory capacity, and expectations on inattention blindness. *Perception* 45, 386–399. doi: 10.1177/0301006615614465
- Kreitz, C., Furley, P., Simons, D. J., and Memmert, D. (2016b). Does working memory capacity predict cross-modally induced failures of awareness? *Conscious. Cognit.* 39, 18–27. doi: 10.1016/j.concog.2015.11.010
- Krol, L. R., Haselager, P., and Zander, T. O. (2019). Cognitive and affective probing: a tutorial and review of active learning for neuroadaptive technology. *J. Neural Eng.* 17:012001. doi: 10.1088/1741-2552/ab5bb5
- Lee, J. D. (2014). Dynamics of driver distraction: the process of engaging and disengaging. *Ann. Adv. Automot. Med.* 58:24.
- Lee, S., Kim, M., Choi, S., and You, H. (2018). Evaluation of a motion seat system for reduction of a driver's passive task-related (tr) fatigue. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 62, 1843–1847. doi: 10.1177/1541931218621420
- Lees, M. N., Cosman, J. D., Lee, J. D., Rizzo, M., and Fricke, N. (2010). Translating cognitive neuroscience to the driver's operational environment: a neuroergonomics approach. *Am. J. Psychol.* 123:391. doi: 10.5406/amerjpsyc.124.4.0391
- Leite, J., Carvalho, S., Fregni, F., and Gonçalves, O. F. (2011). Task-specific effects of tDCS-induced cortical excitability changes on cognitive and motor sequence set shifting performance. *PLoS ONE* 6:e24140. doi: 10.1371/journal.pone.0024140
- Leontiev, A. N. (2014). *Activity and Consciousness*. Moscow: Progress Publishers.
- Lewis, B. A., Eisert, J. L., and Baldwin, C. L. (2014). Effect of tactile location, pulse duration, and interpulse interval on perceived urgency. *Transport. Res. Rec.* 2423, 10–14. doi: 10.3141/2423-02
- Lie, C. H., Specht, K., Marshall, J. C., and Fink, G. R. (2006). Using fMRI to decompose the neural processes underlying the Wisconsin Card Sorting Test. *NeuroImage* 30, 1038–1049. doi: 10.1016/j.neuroimage.2005.10.031
- Mallat, C., Cegarra, J., Calmettes, C., and Capa, R. L. (2019). A curvilinear effect of mental workload on mental effort and behavioral adaptability: an approach with the pre-ejection period. *Hum. Fact.* [Epub ahead of print].
- Mandrick, K., Chua, Z., Causse, M., Perrey, S., and Dehais, F. (2016). Why a comprehensive understanding of mental workload through the measurement of neurovascular coupling is a key issue for neuroergonomics? *Front. Hum. Neurosci.* 10:250. doi: 10.3389/fnhum.2016.00250
- Marois, R., Yi, D. J., and Chun, M. M. (2004). The neural fate of consciously perceived and missed events in the attentional blink. *Neuron* 41, 465–472. doi: 10.1016/s0896-6273(04)00012-1
- Mason, M. F., Norton, M. I., Van Horn, J. D., Wegner, D. M., Grafton, S. T., and Macrae, C. N. (2007). Wandering minds: the default network and stimulus-independent thought. *Science* 315, 393–395. doi: 10.1126/science.1131295
- Mathewson, K. E., Gratton, G., Fabiani, M., Beck, D. M., and Ro, T. (2009). To see or not to see: prestimulus  $\alpha$  phase predicts visual awareness. *J. Neurosci.* 29, 2725–2732. doi: 10.1523/jneurosci.3963-08.2009
- Mathews, G. (2002). Towards a transactional ergonomics for driver stress and fatigue. *Theor. Issues Ergon. Sci.* 3, 195–211. doi: 10.1080/14639220210124120
- Mathews, 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. doi: 10.1037/1528-3542.2.4.315
- Mathews, G., Reinerman-Jones, L. E., Barber, D. J., and Abich, J. IV (2015). The psychometrics of mental work-load: multiple measures are sensitive but divergent. *Hum. Fact.* 57, 125–143. doi: 10.1177/0018720814539505
- Mathews, G., Warm, J. S., Reinerman, L. E., Langheim, L. K., and Saxby, D. J. (2010). "Task engagement, attention, and executive control," in *Handbook of Individual Differences in Cognition*, eds A. Gruszka, G. Matthews, and B. Szymura (Berlin: Springer), 205–230. doi: 10.1007/978-1-4419-1210-7\_13
- May, J. F., and Baldwin, C. L. (2009). Driver fatigue: the importance of identifying causal factors of fatigue when considering detection and countermeasure technologies. *Transport. Res. Part F Traff. Psychol. Behav.* 12, 218–224. doi: 10.1016/j.trf.2008.11.005
- McIntire, L. K., McKinley, R. A., Goodyear, C., and Nelson, J. (2014). A comparison of the effects of transcranial direct current stimulation and caffeine on vigilance and cognitive performance during extended wakefulness. *Brain Stimul.* 7, 499–507. doi: 10.1016/j.brs.2014.04.008
- McKendrick, R., Parasuraman, R., and Ayaz, H. (2015). Wearable functional near infrared spectroscopy (fNIRS) and transcranial direct current stimulation (tDCS): expanding vistas for neurocognitive augmentation. *Front. Syst. Neurosci.* 9:27. doi: 10.3389/fnsys.2015.00027
- Mehta, R. K., and Parasuraman, R. (2013). Neuroergonomics: a review of applications to physical and cognitive work. *Front. Hum. Neurosci.* 7:889. doi: 10.3389/fnhum.2013.00889
- Modi, H. N., Singh, H., Orihuela-Espina, F., Athanasiou, T., Fiorentino, F., Yang, G. Z., et al. (2018). Temporal stress in the operating room: brain engagement promotes "coping" and disengagement prompts "choking". *Ann. Surg.* 267, 683–691. doi: 10.1097/sla.0000000000002289
- Modi, H. N., Singh, H., Yang, G. Z., Darzi, A., and Leff, D. R. (2017). A decade of imaging surgeons' brain function (part I): terminology, techniques, and clinical translation. *Surgery* 162, 1121–1130. doi: 10.1016/j.surg.2017.05.021
- Molloy, K., Griffiths, T. D., Chait, M., and Lavie, N. (2015). Inattention deafness: visual load leads to time-specific suppression of auditory evoked responses. *J. Neurosci.* 35, 16046–16054. doi: 10.1523/jneurosci.2931-15.2015
- Moray, N. (1979). *Mental Workload: Its Theory and Measurement*. New York, NY: Plenum.
- Munakata, Y., Herd, S. A., Chatham, C. H., Depue, B. E., Banich, M. T., and O'Reilly, R. C. (2011). A unified framework for inhibitory control. *Trends Cognit. Sci.* 15, 453–459. doi: 10.1016/j.tics.2011.07.011
- Murphy, S., and Dalton, P. (2016). Out of touch? Visual load induces inattention numbness. *J. Exp. Psychol.* 42, 761. doi: 10.1037/xhp0000218
- Nagahama, Y., Okina, T., Suzuki, N., Nabatame, H., and Matsuda, M. (2005). The cerebral correlates of different types of perseveration in the Wisconsin Card Sorting Test. *J. Neurol. Neurosurg. Psychiatry* 76, 169–175. doi: 10.1136/jnnp.2004.039818
- Navarro, J., Mars, F., Forzy, J. F., El-Jaafari, M., and Hoc, J. M. (2010). Objective and subjective evaluation of motor priming and warning systems applied to lateral control assistance. *Accident Anal. Prevent.* 42, 904–912. doi: 10.1016/j.aap.2009.07.008
- Navon, D. (1984). Resources - a theoretical soupstone? *Psychol. Rev.* 91, 216–234.
- Navon, D., and Gopher, D. (1979). On the economy of the human-processing system. *Psychol. Rev.* 86, 214–225.
- Nelson, J., McKinley, R. A., Phillips, C., McIntire, L., Goodyear, C., Kreiner, A., et al. (2016). The effects of transcranial direct current stimulation (tDCS) on multitasking throughput capacity. *Front. Hum. Neurosci.* 10:589.
- Nelson, J. M., McKinley, R. A., McIntire, L. K., Goodyear, C., and Walters, C. (2015). Augmenting visual search performance with transcranial direct



- current stimulation (tDCS). *Milit. Psychol.* 27, 335–347. doi: 10.1037/mil0000085
- Nelson, J. T., McKinley, R. A., Golob, E. J., Warm, J. S., and Parasuraman, R. (2014). Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). *Neuroimage* 85, 909–917. doi: 10.1016/j.neuroimage.2012.11.061
- Ninomiya, T., Noritake, A., Ullsperger, M., and Isoda, M. (2018). Performance monitoring in the medial frontal cortex and related neural networks: from monitoring self actions to understanding others' actions. *Neurosci. Res.* 137, 1–10. doi: 10.1016/j.neures.2018.04.004
- Norman, D. A., and Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognit. Psychol.* 7, 44–64. doi: 10.1016/0010-0285(75)90004-3
- O'Connell, R. G., Dockree, P. M., Robertson, I. H., Bellgrove, M. A., Foxe, J. J., and Kelly, S. P. (2009). Uncovering the neural signature of lapsing attention: electrophysiological signals predict errors up to 20 s before they occur. *J. Neurosci.* 29, 8604–8611. doi: 10.1523/jneurosci.5967-08.2009
- O'Donnell, R. D., and Eggemeier, F. T. (1986). "Workload assessment methodology," in *Handbook of Human Perception and Performance*, Vol. 2, eds K. Boff, L. Kaufman, and J. P. Thomas (New York, NY: Wiley), 42.1–42.49.
- Oei, N. Y., Veer, I. M., Wolf, O. T., Spinhoven, P., Rombouts, S. A., and Elzinga, B. M. (2012). Stress shifts brain activation towards ventral 'affective' areas during emotional distraction. *Soc. Cognit. Affect. Neurosci.* 7, 403–412. doi: 10.1093/scan/nsr024
- O'Hare, D., and Smitheram, T. (1995). Pressing-on into deteriorating conditions: an application of behavioral decision theory to pilot decision making. *Int. J. Aviat. Psychol.* 5, 351–370. doi: 10.1207/s15327108ijap0504\_2
- Orasanu, J., Martin, L., Davison, J., and Null, C. H. (1998). *Errors in Aviation Decision Making: Bad Decisions or Bad Luck?* Moffett Field, CA: NASA Ames Research Center.
- Palumbo, R. V., Marraccini, M. E., Weyandt, L. L., Wilder-Smith, O., McGee, H. A., Liu, S., et al. (2017). Interpersonal autonomic physiology: a systematic review of the literature. *Personal. Soc. Psychol. Rev.* 21, 99–141. doi: 10.1177/1088868316628405
- Parasuraman, R. (2003). Neuroergonomics: research and practice. *Theor. Issues Ergon. Sci.* 4, 5–20. doi: 10.1080/14639220210199753
- Parasuraman, R., and Rizzo, M. (2008). *Neuroergonomics: The Brain at Work*, 1st Edn. New York, NY: Oxford University Press, Inc.
- Parasuraman, R., and Wilson, G. F. (2008). Putting the brain to work: neuroergonomics past, present, and future. *Hum. Fact.* 50, 468–474. doi: 10.1518/001872008X288349
- Parasuraman, R., Mouloua, M., and Hilburn, B. (1999). "Adaptive aiding and adaptive task allocation enhance human-machine interaction," in *Automation Technology and Human Performance: Current Research and Trends* (Mahwah, NJ: Erlbaum), 119–123.
- Peavler, W. S. (1974). Pupil size, information overload, and performance differences. *Psychophysiology* 11, 559–566. doi: 10.1111/j.1469-8986.1974.tb01114.x
- Pecher, C., Quaireau, C., Lemerrier, C., and Cellier, J.-M. (2011). The effects of inattention on selective attention: how sadness and ruminations alter attention functions evaluated with the attention network test. *Rev. Eur. Psychol. Appl. Eur. Rev. Appl. Psychol.* 61, 43–50. doi: 10.1016/j.era.2010.10.003
- Pepin, G., Malin, S., Navarro, J., Fort, A., Jallaiz, C., Moreau, F., et al. (2016). "Detection of mind-wandering in driving: contributions of cardiac measurement and eye movements," in *Proceedings of the 1st International Neuroergonomics Conference: The Brain at Work and in Everyday Life*, Amsterdam: Elsevier.
- Pessoa, L., and Ungerleider, L. G. (2004). Neuroimaging studies of attention and the processing of emotion-laden stimuli. *Prog. Brain Res.* 144, 171–182. doi: 10.1016/s0079-6123(03)14412-3
- Petersen, S. E., and Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Ann. Rev. Neurosci.* 35, 73–89. doi: 10.1146/annurev-neuro-062111-150525
- Peysakhovich, V., Lefrançois, O., Dehais, F., and Causse, M. (2018). The neuroergonomics of aircraft cockpits: the four stages of eye-tracking integration to enhance flight safety. *Safety* 4:8. doi: 10.3390/safety4010008
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clin. Neurophysiol.* 118, 2128–2148. doi: 10.1016/j.clinph.2007.04.019
- Pope, A. T., Bogart, E. H., and Bartolome, D. S. (1995). Biocybernetic system evaluates indices of operator engagement in automated task. *Biol. Psychol.* 40, 187–195. doi: 10.1016/0301-0511(95)05116-3
- Posner, M. I. (2012). Imaging attention networks. *Neuroimage* 61, 450–456. doi: 10.1016/j.neuroimage.2011.12.040
- Posner, M. I., and Dehaene, S. (1994). Attentional networks. *Trends Neurosci.* 17, 75–79.
- Posner, M. I., and Petersen, S. E. (1990). The attention system of the human brain. *Annu. Rev. Neurosci.* 13, 25–42.
- Posner, M. I., and Tudela, P. (1997). Imaging resources. *Biol. Psychol.* 45, 95–107.
- Pourtois, G., De Pretto, M., Hauert, C. A., and Vuilleumier, P. (2006). Time course of brain activity during change blindness and change awareness: performance is predicted by neural events before change onset. *J. Cognit. Neurosci.* 18, 2108–2129. doi: 10.1162/jocn.2006.18.12.2108
- Pribram, K. H., and McGuinness, D. (1975). Arousal, activation, and effort in the control of attention. *Psychol. Review* 82:116. doi: 10.1037/h0076780
- Prinzl, L. J. III (2002). *Research on Hazardous States of Awareness and Physiological Factors in Aerospace Operations. Report No. NASA/TM-2002-211444*. Washington, DC: NASA.
- Prinzl, L. J., Freeman, F. G., Scerbo, M. W., Mikulka, P. J., and Pope, A. T. (2000). A closed-loop system for examining psychophysiological measures for adaptive task allocation. *Int. J. Aviat. Psychol.* 10, 393–410. doi: 10.1207/s15327108ijap1004\_6
- Proulx, G. (2001). "Occupant behaviour and evacuation," in *Proceedings of the 9th International Fire Protection Symposium* (Iceland: Iceland Fire Authority), 219–232.
- Puschmann, S., Sandmann, P., Ahrens, J., Thorne, J., Weerden, R., Klump, G., et al. (2013). Electrophysiological correlates of auditory change detection and change deafness in complex auditory scenes. *Neuroimage* 75, 155–164. doi: 10.1016/j.neuroimage.2013.02.037
- Qin, S., Hermans, E. J., van Marle, H. J., Luo, J., and Fernandez, G. (2009). Acute psychological stress reduces working memory-related activity in the dorsolateral prefrontal cortex. *Biol. Psychiatry* 66, 25–32. doi: 10.1016/j.biopsych.2009.03.006
- Racz, F. S., Mukli, P., Nagy, Z., and Eke, A. (2017). Increased prefrontal cortex connectivity during cognitive challenge assessed by fNIRS imaging. *Biomed. Opt. Exp.* 8, 3842–3855.
- Ramnani, N., and Owen, A. M. (2004). Anterior prefrontal cortex: insights into function from anatomy and neuroimaging. *Nat. Rev. Neurosci.* 5:184. doi: 10.1038/nrn1343
- Ramsey, N. F., Jansma, J. M., Jager, G., Van Raalten, T., and Kahn, R. S. (2004). Neurophysiological factors in human information processing capacity. *Brain* 127, 517–525. doi: 10.1093/brain/awh060
- Raveh, D., and Lavie, N. (2015). Load-induced inattention deafness. *Attent. Percept. Psychophys.* 77, 483–492. doi: 10.3758/s13414-014-0776-2
- Régis, N., Dehais, F., Rachelson, E., Theoris, C., Pizzoli, S., Causse, M., et al. (2014). Formal detection of attentional tunneling in human operator-automation interactions. *IEEE Trans. Hum. Mach. Syst.* 44, 326–336. doi: 10.1109/thms.2014.2307258
- Regis, N., Dehais, F., Tessier, C., and Gagnon, J.-F. (2012). "Human Factors: a view from an integrative perspective," in *Proceedings HFES Europe Chapter Conference Toulouse 2012*, eds D. De Waard, K. Brookhuis, F. Dehais, C. Weikert, S. Röttger, D. Manzey, et al. (Toulouse: HFES). Available online at: <http://hfes-europe.org>
- Reynal, M., Rister, F., Scannella, S., Wickens, C., and Dehais, F. (2017). "Investigating pilots decision making when facing an unstabilized approach: an eye-tracking study," in *Proceedings of the 19th International Symposium on Aviation Psychology*, Dayton, OH, 335.
- Reyner, L. A., and Horne, J. A. (1998). Evaluation of 'in-car' countermeasures to sleepiness: cold air and radio. *Sleep* 21, 46–51.
- Richter, M., Gendolla, G. H. E., and Wright, R. A. (2016). "Three decades of research on motivational intensity theory: what we have learned about effort and what we still don't know," in *Advances in Motivation Science*, ed. A. J. Elliot (Cambridge, MA: Academic Press), 149–186.
- Ridderinkhof, K. R., Van Den Wildenberg, W. P., Segalowitz, S. J., and Carter, C. S. (2004). Neurocognitive mechanisms of cognitive control: the role of prefrontal cortex in action selection, response inhibition, performance monitoring, and



- reward-based learning. *Brain Cognit.* 56, 129–140. doi: 10.1016/j.bandc.2004.09.016
- Riggs, S. L., and Sarter, N. (2019). Tactile, visual, and crossmodal visual-tactile change blindness: the effect of transient type and task demands. *Hum. Fact.* 61, 5–24. doi: 10.1177/0018720818818028
- Rizzo, M., Robinson, S., and Neale, V. (2007). “The brain in the wild: tracking human behavior in natural and naturalistic settings,” in *Neuroergonomics: The Brain at Work*, eds R. Parasuraman and M. Rizzo (New York, NY: Oxford), 113–130.
- Robbins, T. W., and Arnsten, A. F. (2009). The neuropsychopharmacology of fronto-executive function: monoaminergic modulation. *Annu. Rev. Neurosci.* 32, 267–287. doi: 10.1146/annurev.neuro.051508.135535
- Roy, R. N., and Frey, J. (2016). “Neurophysiological markers for passive brain-computer interfaces,” in *Brain-Computer Interfaces 1: Foundations and Methods* eds M. Clerc, L. Bougrain, and F. Lotte (Hoboken, NJ: John Wiley & Sons), 85–100. doi: 10.1002/9781119144977.ch5
- Russell, D., Statz, J. K., Ramiccio, J., Henderson, M., Still, D., Temme, L., et al. (2016). *Pilot Cueing Synergies for Degraded Visual Environments* (No. USAARL-2016-10). Fort Rucker, AL: US Army Aeromedical Research Laboratory Fort Rucker United States.
- Saint Lot, J., Imbert, J.-P., and Dehais, F. (2020). “Red Alert: a cognitive countermeasure to mitigate attentional tunneling,” in *Proceedings CHI 2020, April 25–30* (Honolulu, HI). doi: 10.1145/3313831.3376709
- Sandson, J., and Albert, M. L. (1984). Varieties of perseveration. *Neuropsychologia* 22, 715–732. doi: 10.1016/0028-3932(84)90098-8
- Sarason, I. G., Sarason, B. R., and Pierce, G. R. (1990). Anxiety, cognitive interference and performance. *J. Soc. Behav. Personal.* 5, 1–18.
- Saravini, F. (1999). “Energy and the brain: facts and fantasies,” in *Mind Myths*, ed. E. Della Salla (Chichester: Wiley), 43–58.
- Sarter, N., and Sarter, M. (2003). Neuroergonomics: opportunities and challenges of merging cognitive neuroscience with cognitive ergonomics. *Theor. Issues Ergon. Sci.* 4, 142–150. doi: 10.1080/1463922021000020882
- Scannella, S., Causse, M., Chauveau, N., Pastor, J., and Dehais, F. (2013). Effects of the audiovisual conflict on auditory early processes. *Int. J. Psychophysiol.* 89, 115–122. doi: 10.1016/j.ijpsycho.2013.06.009
- Scerbo, M. W. (2008). “Adaptive automation,” in *Neuroergonomics: The Brain at Work*, eds R. Parasuraman and M. Rizzo (New York, NY: Oxford), 239–252. doi: 10.1093/acprof:oso/9780195177619.003.0016
- Schneider, W., Dumais, S. T., and Shiffrin, R. M. (1984). “Automatic and control processing and attention,” in *Varieties of Attention*, eds R. Parasuraman and D. R. Davies (Orlando: Academic Press), 1–27.
- Scholte, H. S., Witteveen, S. C., Spekrijse, H., and Lamme, V. A. (2006). The influence of inattention on the neural correlates of scene segmentation. *Brain Res.* 1076, 106–115. doi: 10.1016/j.brainres.2005.10.051
- Schooler, J. W., Smallwood, J., Christoff, K., Handy, T. C., Reichle, E. D., and Sayette, M. A. (2011). Meta-awareness, perceptual decoupling and the wandering mind. *Trends Cognit. Sci.* 15, 319–326.
- Schultz, W. (2002). Getting formal with dopamine and reward. *Neuron* 36, 241–263. doi: 10.1016/s0896-6273(02)00967-4
- Sebok, A., Wickens, C. D., Walters, B., and Fennell, K. (2017). “Alerts on the nextgen flight deck,” in *Proceedings of the 19th International Symposium on Aviation Psychology*, Dayton, OH, 293.
- Selfridge, O. G. (1959). “Pandemonium: a paradigm for learning,” in *Mechanisation of Thought Processes* (London: H.M. Stationery Office), 511–526.
- Senoussi, M., Verdière, K. J., Bovo, A., Ponzoni Carvalho, Chanel, C., Dehais, F., et al. (2017). “Pre-stimulus antero-posterior EEG connectivity predicts performance in a UAV monitoring task,” in *Proceedings of 2016 International Conference on Systems, Man, and Cybernetics* (Canada: IEEE SMC), 1167–1172.
- Shallice, T., and Burgess, P. (1993). “Supervisory control of action and thought selection,” in *Attention: Selection, Awareness and Control*, eds A. Baddeley and L. Weiskrantz (Oxford: Clarendon Press), 171–187.
- Smallwood, J., Beach, E., Schooler, J. W., and Handy, T. C. (2008). Going awol in the brain: mind wandering reduces cortical analysis of external events. *J. Cognit. Neurosci.* 20, 458–469. doi: 10.1162/jocn.2008.20037
- Smallwood, J., and Schooler, J. W. (2015). The science of mind wandering: empirically navigating the stream of consciousness. *Annu. Rev. Psychol.* 66, 487–518. doi: 10.1146/annurev-psych-010814-015331
- Smith, R. P. (1981). Boredom: a review. *Hum. Fact.* 23, 329–340.
- Souza, P. E., Chanel, C. P. C., Dehais, F., and Givigi, S. (2016). “Towards human-robot interaction: a framing effect experiment,” in *IEEE International Conference on Systems, Man, and Cybernetics*, (Budapest: IEEE SMC), 001929–001934.
- Staal, M. A. (2004). Stress, cognition, and human performance: a literature review and conceptual framework.
- Stamp, K., Fairclough, S., Dobbins, C., and Poole, H. (2019). “A neuroadaptive approach to analgesic gaming,” in *The Second Neuroadaptive Technology Conference*, Liverpool, 19.
- Stephens, C., Dehais, F., Roy, R. N., Harrivel, A., Last, M. C., Kennedy, K., et al. (2018). “Biocybernetic adaptation strategies: machine awareness of human engagement for improved operational performance,” in *International Conference on Augmented Cognition*, Copenhagen, 89–98. doi: 10.1007/978-3-319-91470-1\_9
- Taillard, J., Capelli, A., Sagaspe, P., Anund, A., Akerstedt, T., and Philip, P. (2012). In-car nocturnal blue light exposure improves motorway driving: a randomized controlled trial. *PLoS ONE* 7:e46750. doi: 10.1371/journal.pone.0046750
- Thomas, L. C., and Wickens, C. D. (2004). Eye-tracking and individual differences in off-normal event detection when flying with a synthetic vision system display. *Proc. Hum. Fact. Ergon. Soc. Annu. Meet.* 48, 223–227. doi: 10.1177/154193120404800148
- Todd, J. J., Fougny, D., and Marois, R. (2005). Visual short-term memory load suppresses temporo-parietal junction activity and induces inattention blindness. *Psychol. Sci.* 16, 965–972. doi: 10.1111/j.1467-9280.2005.01645.x
- Tomblu, M. N., Asplund, C. L., Dux, P. E., Godwin, D., Martin, J. W., and Marois, R. (2011). A unified attentional bottleneck in the human brain. *Proc. Natl. Acad. Sci. U.S.A.* 108, 13426–13431. doi: 10.1073/pnas.1103583108
- Tracy, J. I., Mohamed, F., Faro, S., Tiver, R., Pinus, A., Bloomer, C., et al. (2000). The effect of autonomic arousal on attentional focus. *Neuroreport* 11, 4037–4042. doi: 10.1097/00001756-200012180-00027
- Tsai, Y.-F., Viirre, E., Strychacz, C., Chase, B., and Jung, T.-P. (2007). Task performance and eye activity: predicting be- havior relating to cognitive workload. *Aviat. Space Environ. Med.* 78, B176–B185.
- Ullsperger, M., Danielmeier, C., and Jocham, G. (2014). Neurophysiology of performance monitoring and adaptive behavior. *Physiol. Rev.* 94, 35–79. doi: 10.1152/physrev.00041.2012
- Ullsperger, M., Nittono, H., and von Cramon, D. Y. (2007). When goals are missed: dealing with self-generated and externally induced failure. *NeuroImage* 35, 1356–1364. doi: 10.1016/j.neuroimage.2007.01.026
- Unsworth, N., and Engle, R. W. (2007). The nature of individual differences in working memory capacity: active maintenance in primary memory and controlled search from secondary memory. *Psychol. Rev.* 114, 104. doi: 10.1037/0033-295x.114.1.104
- Uzzaman, S., and Joordens, S. (2011). The eyes know what you are thinking: eye movements as an objective measure of mind wandering. *Conscious. Cognit.* 20, 1882–1886. doi: 10.1016/j.concog.2011.09.010
- Van Acker, B. B., Parmentier, D. D., Vlerick, P., and Saldien, J. (2018). Understanding mental workload: from a clarifying concept analysis toward an implementable framework. *Cognit. Technol. Work* 20, 351–365. doi: 10.1007/s10111-018-0481-3
- Van Dongen, H., Belenky, G., and Krueger, J. M. (2011). A local, bottom-up perspective on sleep deprivation and neurobehavioral performance. *Curr. Top. Med. Chem.* 11, 2414–2422. doi: 10.2174/156802611797470286
- Verwey, W. B., and Zaidel, D. M. (1999). Preventing drowsiness accidents by an alertness maintenance device. *Accident Anal. Prevent.* 31, 199–211. doi: 10.1016/s0001-4575(98)00062-1
- Vijayraghavan, S., Wang, M., Birnbaum, S. G., Williams, G. V., and Arnsten, A. F. (2007). Inverted-U dopamine D1 receptor actions on prefrontal neurons engaged in working memory. *Nat. Neurosci.* 10:376. doi: 10.1038/nn1846
- Weinmann, M., Schneider, C., and vom Brocke, J. (2016). Digital nudging. *Bus. Inform. Syst. Eng.* 58, 433–436. doi: 10.1007/s12599-016-0453-1
- Weissman, D. H., Roberts, K. C., Visscher, K. M., and Woldorff, M. G. (2006). The neural bases of momentary lapses in attention. *Nat. Neurosci.* 9:971. doi: 10.1038/nn1727
- Wickens, C. D. (1980). The structure of attentional resources. *Atten. Perform. VIII* 8, 239–257.
- Wickens, C. D. (1984). “Processing resources in attention,” in *Varieties of Attention*, eds R. Parasuraman and D. R. Davies (London: Academic Press), 63–101.

- Wickens, C. D. (2002). Multiple resources and performance prediction. *Theor. Issues Ergon. Sci.* 3, 150–177.
- Wickens, C. D. (2005). Attentional tunneling and task management. *Int. Symp. Aviat. Psychol.* 812–817.
- Wickens, C. D. (2008). Multiple resources and mental work-load. *Hum. Fact.* 50, 449–455.
- Wickens, C. D., and Liu, Y. (1988). Codes and modalities in multiple resources: a success and a qualification. *Hum. Fact.* 30, 599–616. doi: 10.1177/001872088803000505
- Wickens, C. D., and Tsang, P. (2014). “Workload,” in *Handbook of Human-Systems Integration*, ed. F. Durso (Washington, DC: APA).
- Wickens, J. R., Horvitz, J. C., Costa, R. M., and Killcross, S. (2007). Dopaminergic mechanisms in actions and habits. *J. Neurosci.* 27, 8181–8183. doi: 10.1523/jneurosci.1671-07.2007
- Wierwille, W. W., and Eggemeier, F. T. (1993). Recommendation for mental workload measurement in a test and evaluation environment. *Hum. Fact.* 35, 263–281. doi: 10.1177/001872089303500205
- Yeh, Y. Y., and Wickens, C. D. (1988). Dissociation of performance and subjective measures of workload. *Hum. Fact.* 30, 111–120. doi: 10.1177/001872088803000110
- Yerkes, R. M., and Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit formation. *J. Compar. Physiol. Psychol.* 18, 459–482. doi: 10.1002/cne.920180503
- Young, M. S., Brookhuis, K. A., Wickens, C. D., and Hancock, P. A. (2015). State of science: mental workload in ergonomics. *Ergonomics* 58, 1–17. doi: 10.1080/00140139.2014.956151
- Young, M. S., and Stanton, N. A. (2002). Malleable attentional resources theory: a new explanation for the effects of mental underload on performance. *Hum. Fact.* 44, 365–375. doi: 10.1518/0018720024497709
- Zander, T. O., and Kothe, C. (2011). Towards passive brain–computer interfaces: applying brain–computer interface technology to human–machine systems in general. *J. Neural Eng.* 8:025005. doi: 10.1088/1741-2560/8/2/025005
- Zaneboni, J., and Saint-Jalmes, B. (2016). *U.S. Patent No. 9,302,779*. Washington, DC: U.S. Patent and Trademark Office.

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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