Momentary lapse of control: A cognitive continuum approach to understanding and mitigating perseveration in human error

Frédéric Dehais[1*], Helen M. Hodgetts[2,3], Mickael Causse[1], Julia Behrend[1,5,] Gautier Durantin[4], & Sébastien Tremblay[3]

[1] ISAE-SUPAERO, Université de Toulouse, 10 avenue Edouard Belin, 31055, Toulouse, France

[2] Department of Applied Psychology, Cardiff Metropolitan University, Cardiff, CF5 2YB, UK

[3] École de psychologie, Université Laval, Québec (QC), G1V 0A6, Canada.

[4] School of Information Technology and Electrical Engineering, University of Queensland, Brisbane QLD 4072, Australia

[5] Laboratoire de Neurosciences Cognitives, Inserm unit 960, Département d'Etudes Cognitives, Ecole Normale Supérieure, PSL Research University, 75005 Paris, France

*Corresponding author: Frédéric Dehais, ISAE-SUPAERO, Université de Toulouse, 10 avenue Edouard Belin, 31055 Toulouse, France. E-mail: Frederic.Dehais@isae.fr

Abstract

Everyday complex and stressful real-life situations can overwhelm the human brain to an extent that the person is no longer able to accurately evaluate the situation and persists in irrational actions or strategies. Safety analyses reveal that such perseverative behavior is exhibited by operators in many critical domains, which can lead to potentially fatal incidents. There are neuroimaging evidences of changes in healthy brain functioning when engaged in non-adaptive behaviors that are akin to executive deficits such as perseveration shown in patients with brain lesion. In this respect, we suggest a cognitive continuum whereby stressors can render the healthy brain temporarily impaired. We show that the dorsolateral prefrontal cortex is a key structure for executive and attentional control whereby any transient (stressors, neurostimulation) or permanent (lesion) impairment compromises adaptive behavior. Using this neuropsychological insight, we discuss solutions involving training, neurostimulation, and the design of cognitive countermeasures for mitigating perseveration.

Keywords

Perseveration; DLPFC impairment; human error; executive control; attentional control; cognitive countermeasures;

Introduction

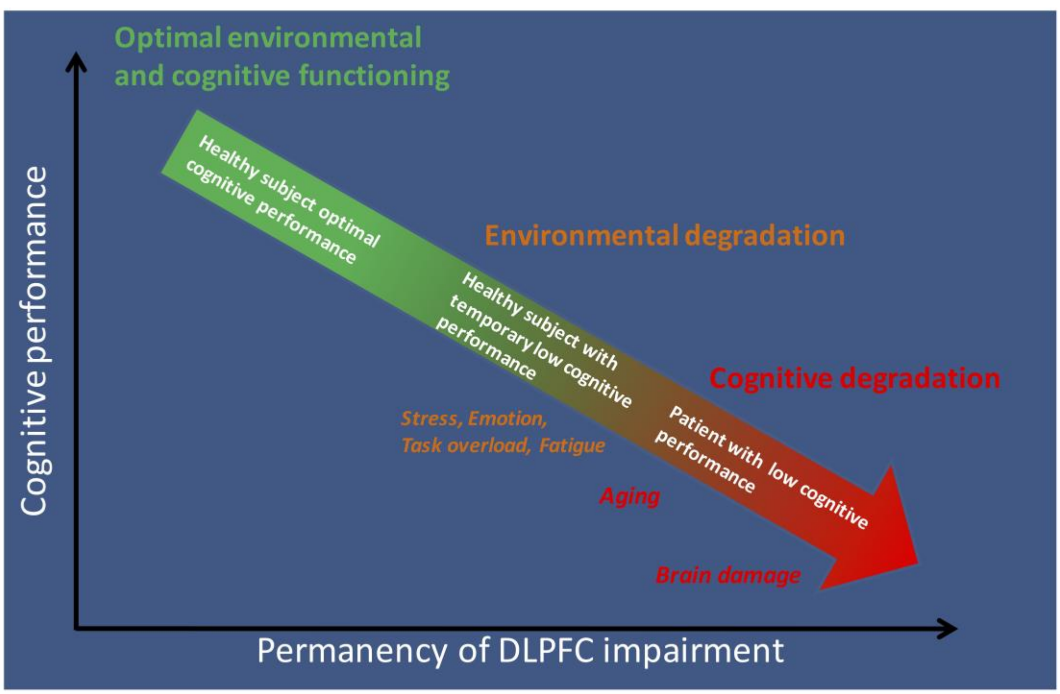
Operators of critical systems (e.g. an airplane, unmanned vehicle, nuclear power plant) are subjected to numerous factors known to impair human cognitive performance (e.g., overload, fatigue, emotional stressors), as well as having to contend with external distractions and interruptions that can further reduce situation awareness (e.g., Hodgetts, Vachon, & Tremblay, 2014; Hodgetts et al., 2005). Such complex activities require adaptive behavior to deal with dynamic and uncertain situations, yet safety analysis highlights that even the most experienced human operators can persist in inappropriate courses of action when overwhelmed by unexpected events. In most of these highly degraded but often recoverable situations, operators are unable to comprehend the situation and persist in erroneous behaviors despite the occurrence of multiple visual/auditory cues that should instigate a change in strategy. This kind of behavior in which operators make decisions without reevaluating whether or not they are correct – even in the face of information that directly contradicts their decision – has been coined perseveration (Hall, Fragola, & Wreathal, 1982). Such a lack of mental flexibility is seen with dysexecutive patients in the clinical domain, but in the current paper we seek to provide a holistic account for perseveration to help advance our understanding of human performance failures in the real world. We identify how neural correlates of perseverative behavior can be compromised by either situational variables or brain damage particularly to the dorslolateral prefrontal cortex (DLPFC), and propose a cognitive continuum whereby perseveration can result from a brain lesion or from a temporary loss of control as a function of environmental stressors in safety-critical operations. The current article is not intended as an exhaustive review of the perseveration literature; rather, we provide examples from clinical and cognitive psychology to illustrate the proposed cognitive continuum and refer the reader elsewhere for more comprehensive reviews of perseverative behaviours (e.g., Clancy, Prestwich, Caperon, & O'Connor, 2016; Hauser, 1999; Hotz & Helm-Estabrooks, 1995), as well as complementary approaches, for example, from social psychology (Fox & Hoffman, 2002) and ergonomics (De Keyser & Woods, 1990).

In the neuropsychological domain, the concept of perseveration is the continuation or repetition of an action or a strategy after the cessation of the original stimulus or goal, and to an extent that the activity is no longer optimal or relevant to the task at hand (Sandson & Albert, 1984). More precisely, these authors defined three categories of perseveration: recurrent, continuous, and, of most relevance to the current human factors focus, stuck-in-set perseveration. It is defined as “the inappropriate maintenance of a current category or framework”, and is considered a process deficit in executive functioning. This inability to shift between representations and strategy, observed in patients (Waegeman, Declerck, Boone, Seurinck, & Parizel, 2014), is commonly assessed with the Wisconsin Card Sorting Test (WCST; Berg, 1948) whereby cards must be sorted according to implicit rules that change across time. This ability to adapt strategy in line with changing circumstances is important in everyday situations, and particularly for the operators of dynamic and complex critical systems. For example, piloting an airplane involves adaptation to continually evolving scenarios, and mental flexibility as measured by one of the performance metrics on the WCST has proven successful in predicting pilot perseveration in a subsequent flight simulation (Causse, Dehais, Arexis, & Pastor, 2011). A correlation was found between the total number of errors (including perseverative errors) and a pilot's erroneous decision to continue to land in bad weather. This suggests that impaired performance on the WCST can be indicative of non-adaptive perseveration in pilots as well as in the aforementioned patient population, supporting the idea of common neural correlates underlying different manifestations of perseverative behavior.

Research from areas of cognitive psychology (Lee, 2014), cognitive neuroscience (Dreisbach et al., 2004) and social psychology (Atkinson & Cartwright, 1964; Masicampo & Baumeister, 2011) have identified certain pre-conditions that can lead healthy people to rigidly pursue their initial goal even if it would seem maladaptive. One main explanation for this phenomenon is that any interference with the on-going activity (Dehais, Causse, & Tremblay, 2012) can induce a feeling of loss that leads to increased physiological arousal and prefrontal activity (Yechiam, & Hochman, 2013), which serves to focus attention on task achievement. This focus promotes a fixation on the initial goal to the exclusion of other viable alternatives. Several factors are thought to increase the likelihood of this type of human error, including high task demand (Durantin, Gagnon, Tremblay, & Dehais, 2014; Dehais, Causse, Vachon, & Tremblay, 2012), time-on-task (Van der Linden, Frese, & Meijman, 2003; Cho, Ennaceur, Cole, & Suh, 2000; Orzeł-Gryglewska Jolanta, 2010; Rouch, Wild, Ansiau, & Marquié, 2005), and stress and emotions (Shanteau, & Dino, 1993; Cowen, 1952). These pre-conditions are endemic in the work environments of critical systems that are analogous with multitasking, time pressure, emotional stress, and in some cases, under stimulation (e.g., supervisory monitoring/vigilance, such as air traffic control), making these tasks particularly susceptible to perseverative error. A greater understanding of the neural basis of perseveration could inform strategies or support systems that could help to mitigate this class of human error.

Despite the development of technology to automate aspects of the work environment and circumvent the fallibility of human operators, human error – and in particular perseverative error – remains a key feature of many real world catastrophic events. The history of aviation is unfortunately rich with perseverative behaviors such as the 1978 United Air Lines Flight 173 incident in which the pilots faced a faulty landing gear indicator and decided to postpone the landing with a holding pattern. The pilots became so fixated on handling the landing gear issue that they forgot to check the fuel tank instrument and eventually crashed in the vicinity of Portland airport (NTSB, 1979). In the medical domain, Bromiley (2008) described how his wife died following “routine” surgery: during anesthesia, the medical team faced a “can’t intubate, can’t ventilate” situation as they were trying to intubate the patient. While a solution to this situation exists (tracheotomy), the team ignored it and persisted in unsuccessful attempts at intubating for 35 minutes before abandoning the procedure, after which time the patient could not recover. These dramatic events are not specific to these fields, and such critical persistence in inappropriate behaviors has occurred in the nuclear power plant industry (e.g., Three Mile Island, Tchernobyl), the Aerospace domain (e.g., Challenger accident; Rogers, 1986) and has been observed with anesthesiologists (Fioratou, Flin, & Glavin, 2010; Gaba, 1989; Schwid & O’Donnell, 1992), drivers (Lee, 2014), traders (Haigh & List, 2005), navy operators (Collyer & Malecki, 1998; Rochlin, 1991), surveillance and monitoring operators (Hodgetts, Vachon, Chamberland, & Tremblay, 2017; Lanagan-Leitzel, Skow, & Moore, 2015) and athletes in extreme sport (Krakauer, 1997). The ubiquity of these behaviors across varied domains raises the question of how highly trained personnel can become 'trapped' and fail to respond appropriately, despite being presented with cues that should prompt an alternative course of action.

The existence of perseverative behavior at the core of these real-world incidents supports the idea that environmental factors may cause an impairment of executive and attentional control within healthy operators, leading to deficits similar to those observed in patients with brain lesions. The boundary between normal and pathological cognitive performance can be crossed by a healthy individual, depending on his/her position along a cognitive continuum (see Petersen, 2004, for an illustration of the cognitive continuum in the clinical domain). We therefore suggest that advances in understanding and mitigating human error can be made by considering a cognitive continuum ranging from normal (high to normal intellectual performance) to pathological (very degraded intellectual performance), as a function of the level of mental workload, fatigue, or stress (Figure 1). **Figure 1 about here**



In the sections below, we first review the constructs of perseveration and related executive impairments that can jeopardize the ability to adapt to external changes. In terms of the cognitive continuum hypothesis, we show that permanent or temporary deactivation of the DLPFC area can promote perseveration.

Secondly, we argue that perseveration can result from a lack of attentional control, thereby an erroneous course of action is continued due to an inability to notice relevant environmental changes that could indicate the need for an alternative approach. We review studies investigating temporal, parietal and frontal cortices involved in attentional networks within both healthy and patient populations, and note parallels between the two. In particular, we emphasize the key role of the DLPFC, at the interface between executive and attentional control, impairment of which can lead to biased attentional processing and neglect of information with the potential to instigate changes in behavior.

Thirdly, the cognitive continuum can provide a basis for further research and for the development of solutions specifically suited to degraded operational conditions. We therefore introduce a number of methods, such as training, neurostimulation and cognitive countermeasures for mitigating perseverative behavior.

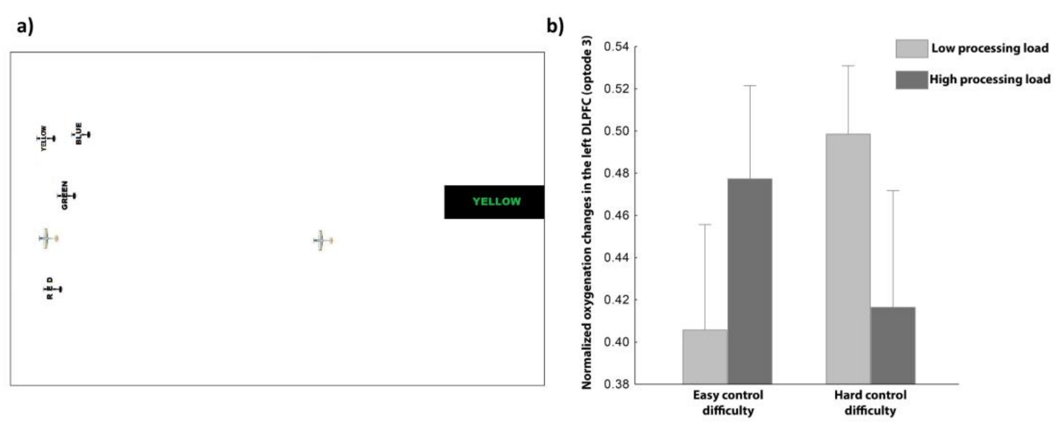
Perseveration: Making the parallel between a neurological deficit and a temporary loss of executive control

The construct of perseveration has been largely studied in the fields of neuropsychology, neurology, and psychiatry with patients exhibiting dysexecutive syndrome (e.g., following brain damage to the frontal lobes); however, as postulated, a similar syndrome also concerns human factors as it appears in healthy operators subjected to environmental stressors. In accordance with the continuum hypothesis, we propose that the manifestation of perseverative behavior in complex task operators is due to the impairment of neural circuits, whereby these circuits are permanently affected in patients (Robertson & Halligan, 1999) and the elderly (Head, Kennedy, Rodrigue, & Raz, 2009; Kennedy & Raz, 2009), or affected temporarily in healthy individuals through operational stressors. In terms of the brain regions involved, neuropsychological studies have shown consistent relationships between perseveration and structural damage in several brain regions of the prefrontal lobes (Anderson, Damasio, Jones, & Tranel, 1991; Lombardi, Andreason, Sirocco, Rio, & Gross, 1999; Nagahama, Okina, Suzuki, Nabatame, & Matsuda, 2005; Ridderinkhof, Span, & van der Molen, 2002), including the DLPFC (Lie, Specht, Marshall, & Fink, 2006).

Neuroimaging evidence supports the idea that temporary disruption of the functioning of the prefrontal lobes induced by environmental stressors is one factor contributing to perseverative error. The transient hypofrontality hypothesis (Dietrich, 2003) postulates that human errors can be linked to a transient deregulation of the prefrontal cortex function induced by high levels of demand. Physically demanding situations have been found to impair prefrontal-dependent cognition, in particular with higher levels of perseverative errors (Del Giorno, Hall, O'Leary, Bixby, & Miller, 2010). Psychological stressors (Dolcos & McCarthy, 2006; Simpson, Drevets, Snyder, Gusnard, & Raichle, 2001; Simpson, Snyder, Gusnard, & Raichle, 2001) are associated with a temporary decrease in activity in the right DLPFC and the promotion of perseverative behavior (Causse et al., 2013). Cognitively demanding tasks have also been found to disengage DLPFC and to induce a lack of mental flexibility (Durantin et al., 2014; see

Figure 2). Furthermore, low-demand and unstimulating tasks are known to impair the ability to adapt to environmental changes (Braboszsz & Delorme 2011; Smallwood, Beach, Schooler, & Handy, 2008, Galéra et al., 2012; Lemercier et al., 2014; Yanko, & Spalek, 2014). Again, in these low-demand and unstimulating environments, perseverative errors have been associated with lower activation of DLPFC (Durantin, Dehais, Delorme, 2015; Harrivel, Weissman, Noll, & Peltier, 2013; Mason et al., 2007). These findings indicate that workload that is either too high (e.g., multitasking, multiple sources of incoming information) or too low (e.g., monitoring/vigilance task with few targets), could contribute to an operator becoming "stuck in set" due to decreased activity in the DLPFC.

Figure 2 about here

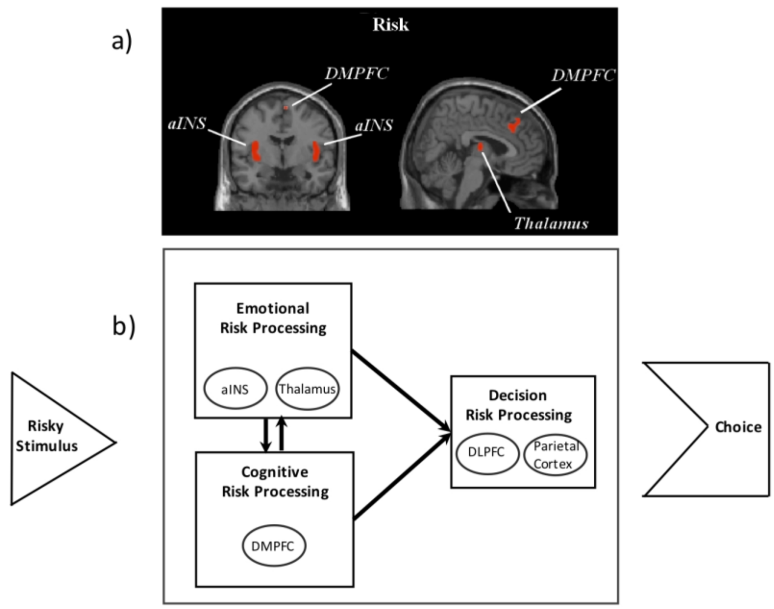


One possible neurochemical explanation for this decreased activity in the DLPFC when facing operational stressors relates to the dopamine and norepinephrine neurotransmitters that have a modulatory influence on PFC activity in a non-linear fashion (see Arnsten, 2010). Low release (i.e. under low arousal) or excessive release (i.e., under high arousal) of these two neuromodulators depresses the firing rates of neurons in the DLPFC and consequently impairs executive functioning. Under low arousal settings, the rationale for DLPFC deactivation may result from a need to prevent the waste of valuable cognitive resources when facing non-challenging tasks. Under high arousal settings, dopamine and noradrenaline – while depressing DLPFC activity – increase the activation of subcortical areas dedicated to promoting the activation of automatic responses (Dolan, 2002). The advantage of engaging an “automatic” strategy is that it protects against depletion of resources, and allows a faster response time when facing an immediate danger, like the “fight-or-flight” response. While such a strategy could be considered adaptive in the early age of humanity or when facing a well-known situation, it is much less appropriate in the face of complex and unknown situations (Ellenbogen, Schwartzman, Stewart, & Walker, 2006) that require executive functions for adaptation (Barkley, 2001).

It is useful to consider several links between the DLPFC and perseverative behavior as these can provide a new perspective for understanding the underlying mechanisms of perseveration in real-world situations with non-clinical populations. First, the DLPFC is a brain structure involved in working memory (WM), an executive function dedicated to storing and updating information (see Curtis & Esposito, 2004). Accordingly, a temporary lack of WM capacity is likely to induce perseveration since the inability to upgrade situation awareness, in line with unexpected events, can lead to the continuation of schemes of action that are no longer appropriate in the current circumstances (Causse, Dehais, Arexis, & Pastor, 2011; Orasanu, Martin, & Davison, 2001). Second, it has been proposed that the DLPFC is the neural substrate of the supervisory attentional system that arbitrates conflicts between competitive responses to stimuli (Norman & Shallice, 1986). In accordance with this perspective, perseveration can be conceptualized as the incapacity to selectively inhibit irrelevant or dominant responses (Fuster, 1988; Houdé, Zago, Mellet, Moutier, & Pineau, 2000; Houdé, 2000), and, hence, manifests the behavioral tendency to persist with the original goal under depressed DLPFC activity. Third, the monitoring capacity of frontal executive functions is an important element for human reasoning, flexibility, and adaptation in open-ended environments (Collins & Koechlin, 2012). The DLPFC is known to play a key role in planning through the assessment of alternative strategies to adapt to external contingencies in naturalistic situations (Donoso, Collins, & Koechlin, 2014). One could argue that the disengagement of this prefrontal area leaves human operators ill-equipped to elaborate upon new solutions, and hence persevering with their initial strategy by default.

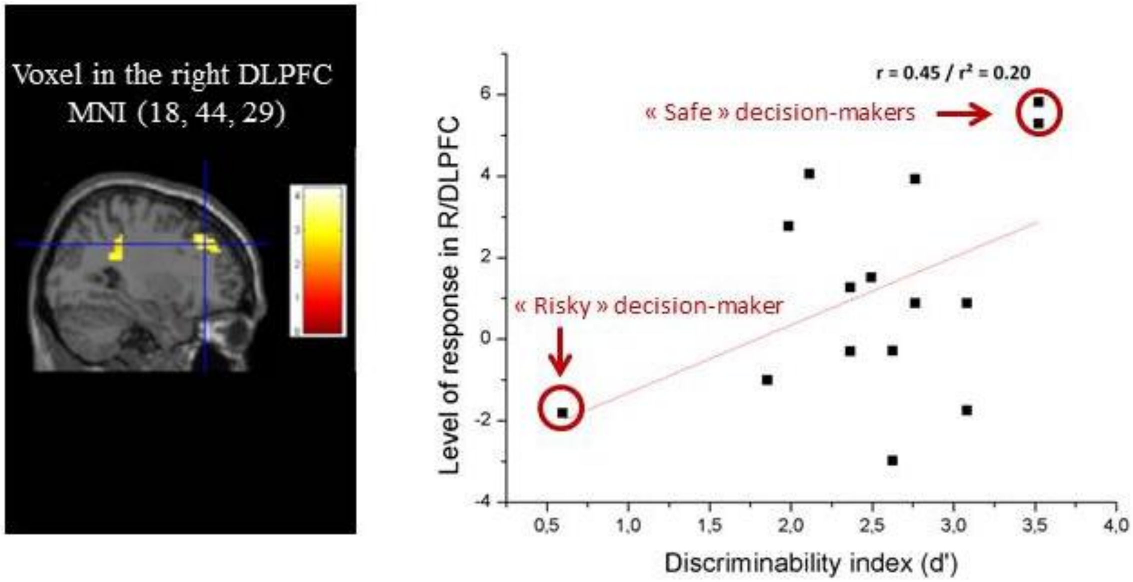
A final point to note in the link between perseveration and the DLPFC is the role of this region for self-regulation and control of goal values, both of which are important for rational-focused decision-making (Gross, 1998). Several fMRI studies have found that the DLPFC is involved in voluntary emotion regulation (Delgado, Gillis, & Phelps, 2008; Ochsner & Gross, 2005) and cognitive control (Hare, Camerer, & Rangel, 2009). Interestingly, Maier, Makwana, and Hare (2015) showed that acute stress manipulations increased immediate reward seeking by impairing self-control decisions with long-term goals. In this study, stress induction was linked to a reduced connectivity between the vmPFC and the DLPFC. Accordingly, the disengagement of the DLPFC might impair the operator's ability to control his/her emotions under unexpected or stressful operational conditions leading him/her to seek immediate options, instead of delayed but safer or more rewarding options. Similarly, perseveration is thought to be related to risk taking (Goh & Wiegmann, 2002) and poor utility assessment and ability to frame decisions (Burian, Orasanu, & Hitt, 2000; O'Hare & Smitheram, 1995). Fecteau et al. (2007) demonstrated that excitatory transcranial direct stimulation of the DLPFC within healthy subjects suppresses the temptation to maximize personal gain whereas disruption of the DLPFC by inhibitory stimulation induces risk-taking behavior (Knoch et al., 2006), and therefore compromises the selection of well-considered and rational strategies. Mohr, Biele, and Heekeren (2010) performed a meta-analysis, presenting a model of the neural correlates involved in the risky decision-making process (Figure 3a). In addition, the authors developed a model (Figure 3b), explaining the risk processing between the risk stimulus and the actual choice. They argued that risky decision processing (DLPFC, parietal cortex) is an interplay of emotional risk processing (thalamus, bilateral anterior insula) and cognitive risk processing (dorso-medial prefrontal cortex).

Figure 3 about here



Consistent with these findings is an fMRI study involving a simplified but plausible landing situation in which participants were to decide whether or not to land (Causse et al., 2013). A payoff matrix was designed to reproduce the aversive consequences linked with the decision to go-around. The behavioral results revealed a shift from rational to risky decision making to land when a financial incentive was present. Participants with poor decision-making performance who adopted more risky and perseverative behaviors exhibited lower activity in the right DLPFC (see Figure 4).

Figure 4 about here



Taken together, these four assertions provide some neuropsychological explanations for perseveration in healthy individuals facing degraded environments, and demonstrate commonalities with frontal lobe patients. However, there is a need for further studies conducted with human operators in safety-critical operations, and a need to consider other neural areas involved in cognitive control (e.g., orbitofrontal cortex and anterior cingulate cortex, see Stuss & Knight, 2013; cortico-basal ganglia circuit, see Dreisbach & Goschke, 2004). Hence, the hypothesis of a putative cognitive continuum, spanning from optimal to impaired performance (Pastor, 1999) represents a promising approach to offer a full account of the complexity of this phenomenon in complex real-life situations.

Perseveration as inattention to task-relevant changes

While we can make the case that perseverative behavior is an executive deficit –

either due to frontal lesions or a temporary change in activity in the DLPFC due to environmental conditions – a complementary approach to conceptualize perseveration within healthy but stressed subjects is to consider the existence of attentional limitations. That is, individuals may fail to adapt to developing circumstances not because they lack the cognitive control or flexibility to assimilate and respond to these changes, but because they are simply unable to detect unexpected changes occurring in the environment in the first place. In this section, we consider examples of how attentional limitations can lead to perseverative behavior, and in accordance with the continuum hypothesis, provide comparison with brain lesion studies.

While the avoidance of extraneous stimuli is often desirable as it protects planned behavior from distraction and impulsivity, it also means that in a dynamic environment, important changes in the evolving situation can be missed (change blindness; Simons & Levin, 1997). Individuals can experience inattentional blindness or change blindness to the extent that they miss critical visual signals that are designed to capture attention and invoke an alternative behavioral response. Change blindness refers to a failure to visually perceive a change in state of a present stimulus, whereas inattentional blindness refers to a failure to visually perceive the appearance of new stimuli (Jensen, Yao, Street, & Simons, 2011). This phenomenon of perceptual failure often occurs under high visual load (Lavie, Beck, & Konstantinou, 2014; Rauss, Pourtois, Vuilleumier, & Schwartz, 2009), and has been reported in a wide range of work domains and operational contexts, affecting the performance of police officers (Chabris, Weinberger, Fontaine, & Simons, 2011), radiologists (Drew, Vol, & Wolfe, 2013), anesthesiologists (Ho et al., 2017), drivers (Strayer, Drews, & Johnston, 2003), surveillance operators (Suss, Vachon, Lafond, & Tremblay, 2015), pilots (Nikolic, Orr, & Sarter, 2004), unmanned-vehicle operators (Dehais, Causse, Vachon, & Tremblay, 2012) and athletes (Memmert & Furley, 2007).

Using fMRI to determine the brain regions involved in such issues of inattention can be challenging due to the difficulty of inducing failures of attention in a repetitive manner. However, two studies, implementing a change detection task using a WM paradigm (Pessoa & Ungerleider, 2004) and a flicker paradigm (Beck, Rees, Frith, & Lavie, 2001), found evidence of fronto-parietal network activation when changes were reported. The authors concluded that activation of the parietal cortex and PFC (including DLPFC) represents a *sine qua non* condition to awareness. Accordingly, the parietal cortex would play a transient role during the occurrence of rapid changes in the environment (i.e. selection of new items) whereas the DLPFC would exert stable and sustained maintenance and manipulation of the selected items in WM (see Rees, 2001). Todd, Fougnie, and Marois (2005) manipulated visual WM load in a primary task to induce inattentional blindness to unexpected visual stimuli. Their results indicated that failures of attention resulted in a deactivation of the right temporo-parietal junction (TPJ). TPJ has been mainly thought to play a key role in exogenous attention and the processing of unexpected stimuli (Fox et al., 2005). Some authors have proposed that the activity of this brain area is suppressed during the performance of demanding goal-driven activities (Todd, Fougnie, & Marois, 2005; Marois, Yi, & Chun, 2004), probably to shield against distraction and depletion of resources. This hypothesis echoes with the attentional set theory postulating that inattentional failures result from the processing of events relevant only to the task at hand (Most et al., 2005).

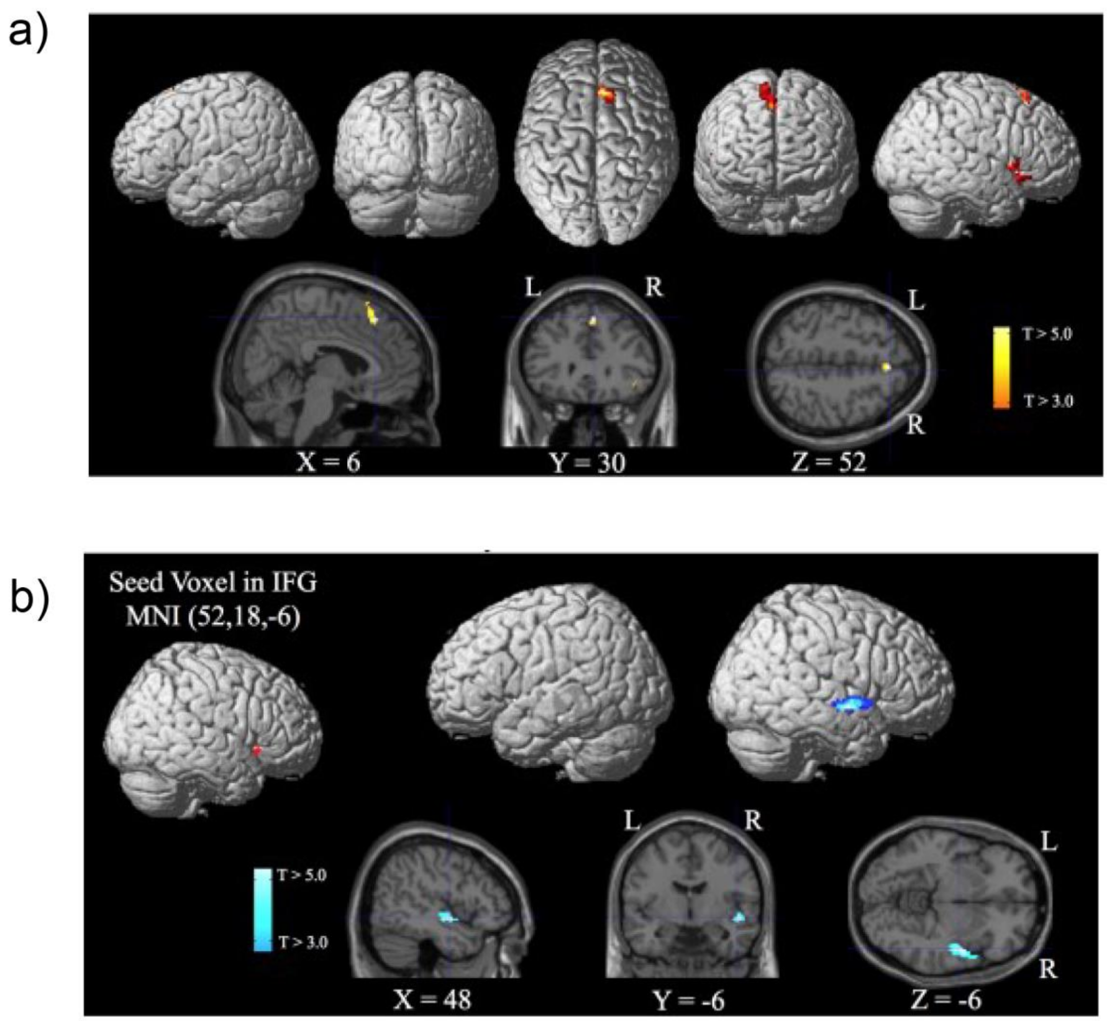
In keeping with the cognitive continuum hypothesis, we consider parallels between the brain regions underlying temporary inattention in the aforementioned experimental studies, and the failures of attention experienced with brain lesions. Patients with lesions of TPJ (Robertson, Lamb, & Knight, 1988; Friedrich, et al., 1998, see Corbetta & Schulman, 2011, for a review) and participants undergoing rTMS to this area (Chang et al., 2013; Meister et al., 2006), are found to experience a failure of attentional reorientation. In terms of DLPFC lesions (patients or rTMS-induced), results regarding the failure of visual attention have been contradictory or non-compelling (Kozuch, 2014). However, a disconnection of white matter fibers between DLPFC and parietal cortices has been shown to alter attentional processing and the reorientation of attention (He et al., 2007). These connectivity analyses confirm that the DLPFC is a crucial node in the voluntary attentional network *(*Corbetta & Shulman, 2002).

The link between issues of inattention and perseverative behavior is also relevant in the auditory modality, as auditory signals designed to promote disengagement from an erroneous strategy can be neglected if poorly designed (Bliss, 2003; Breznitz, 2013; Dekker, 2005; Sorkin, 1988), especially under high workload settings (Bliss & Dunn, 2000), leading operators to persue their original goal. Also, there is now evidence that unexpected or task-irrelevant salient sounds can fail to reach awareness when engaged in stressful (Dehais, Vachon, Causse, & Tremblay, 2014), or cognitively (Causse, Imbert, Giraudet, Jouffrais, & Tremblay, 2016) or visually (Macdonald & Lavie, 2011; Molloy, Griffiths, Chait, & Lavie, 2015; Raveh & Lavie, 2015; Tellinghuisen, Cohen, & Cooper, 2016) demanding situations. This phenomenon of inattentional deafness could provide a valuable explanation for understanding the lack of detection of auditory stimuli reported within anesthesiologists (Brown & Anglin-Regal, 2008; Edworthy, 2013), navy radar operators (Chamberland, Hodgetts, Vallières, Vachon, & Tremblay, 2017) and pilots (Dehais et al., 2012; Dehais et al., 2014; Gibb & Gray, 2016), yielding human operators to make inappropriate decisions and display perseverative behaviors. For instance, the co-pilot of the ill-fated Air France flight 447 from Rio de Janeiro continued to put the aircraft into a steep climb, despite more than 70 audible stall warnings (BEA, 2012).

Cognitive neuroscience has provided some insights into the phenomenon of auditory inattention in the healthy brain. For instance, it has been shown that auditory evoked responses can be suppressed by visual modulatory influences at a very early stage in the brainstem (Sörqvist, Stenfelt, & Rönnberg, 2012) and electrophysiological inattentional deafness studies have revealed evidence of a reduced N100 response in the auditory cortex (Dehais, Roy, & Scannella, 2019; Callan, Gateau, Gonthier, & Dehais, 2018) as well as diminished auditory P300 amplitude (Dehais, Roy, & Scannella, 2019; Giraudet, St-Louis, Scannella, & Causse, 2015), indexing attention orientation. A MEG study reported diminished N100 auditory evoked activity in the superior temporal sulcus (STS) and posterior middle temporal gyrus (MTG) during episodes of inattentional deafness under high perceptual load (Molloy, Griffiths, Chait, & Lavie, 2015). These two integrative areas have been shown to be particularly active for the processing of multimodal stimuli (Beauchamp, Lee, Argall, & Martin, 2004). One recent fMRI experiment (Durantin, Dehais, Gonthier, Terzibas, & Callan, 2017), examining auditory hits vs misses in an ecological inattentional deafness paradigm in the context of flying, proposed the existence of top down regulation mechanisms taking place via the activation of frontal regions associated with an attentional bottleneck described by Tombu et al.

(2011). This study revealed that the onset of this frontal network served to shut down hearing processing via reduced effective connectivity to auditory processing areas in the right MTG and superior temporal gyrus (STG); see Figure 5. Interestingly, the visual area (V5 – related to motion processing) was more active during episodes of inattentional deafness confirming that the visually demanding task (i.e. controlling the aircraft) draws away attention from auditory events.

Figure 5 about here



These transient patterns of cerebral deactivation allow comparison with brain injured patients, revealing the involvement of similar structures. Lesions of STS and STG have been associated with several auditory disorders including impairment of rapid processing and recognition of environmental sounds (see Goll, Crutch, & Warren, 2010 for a review). Knights and Scabini (1988) reported that patients with a unilateral lesion of the STG exhibited lower auditory N100 amplitude compared to healthy subjects in response to auditory stimuli. Electric cortical stimulation of STG on neurosurgical patients has been known since the 1950's to suppress hearing abilities (Penfield & Rasmussen, 1950). The key role of this brain structure for processing sounds has been confirmed more recently with the demonstration that electrical pulses over STG induce transient deafness within neurosurgery patients (Fenoy et al., 2006).

Whereas studies investigating inattentional deafness within healthy participants have shown evidence of the top down prefrontal regulation of attention (Durantin, Dehais, Gonthier, Terzibas, & Callan, 2017; Molloy, Griffiths, Chait, & Lavie, 2015) none have precisely defined the role of the DLPFC. Interestingly, some studies reveal that this brain structure allows for a shift of attention by increasing the activity of the most relevant stream of information with regards to the on-going task (Johnson, & Zatorre, 2006). This mechanism has been demonstrated by impairing DLPFC activity with rTMS in a bimodal paradigm which resulted in the inability to divide and switch attention between visual and auditory modalities (Johnson, Strafella, & Zatorre, 2007).

In the above section, we have demonstrated that attentional control – involving a large network including temporal, parietal and prefrontal cortices – supports adaptive behavior and can be disrupted by brain lesions or operational stressors. Among these cortices, the DLPFC plays a key role in the voluntarily and top down regulation of attention. Following the cognitive continuum approach, we have also demonstrated that permanent or temporary impairments of these attentional networks can impede cross-modal interactions to an extent that auditory signals are missed under demanding visual settings. The opposite also stands true (Strayer, Drews, & Johnston, 2003) as focusing one's attention on the auditory stream (e.g., talking on the phone while crossing a street) can negatively impact visual processing (e.g., detecting approaching traffic). Moreover, these cross-modal issues are not limited to the auditory and visual modalities as failures of attention with other modalities have also been reported (Murphy & Dalton, 2016);however, further connectivity research is necessary to investigate the complex interactions that take place between the neural networks involved in the control of attention and perseveration.

Mitigating Human Performance Limitations

In accordance with the hypothesis of a putative cognitive continuum, we have highlighted some of the neural mechanisms underpinning perseveration at the executive and attentional levels and their deleterious consequences on human performance. Taking into account this clinical framework, an important next step is to implement cognitive countermeasures to mitigate the effect of these critical errors. We first describe potential solutions to improve the executive level impairment and then discuss some potential cognitive countermeasures dedicated to facilitating sensory processing.

The comparison of the neural circuits involved in perseveration at an executive level revealed that perseveration results from impaired activity in the DLPFC. Under these conditions, the brain switches from slow and flexible strategies controlled by the PFC to rapid but rigid automatic responses (Dolan, 2002). While it may be difficult to prevent the use of such automatic actions in high-pressured situations, one option might be to expand the range of automatic responses available for selection in such circumstances. Providing appropriate training using simulated critical events might improve the catalogue of reponses that could help to cope with unexpected situations, thus potentially reducing the likelihood of perseveration despite rigid and automatic responses still taking presidence. Moreover, training represents an important approach since perseverative behavior has been linked with low expertise levels (e.g., novices; Causse, Dehais, & Pastor, 2010), with the suggestion that novices have lower abilities for both information search and problem solving that in turn negatively affect decision making (Wiggins & O'Hare, 1995).

One drawback of direct training is that it is not possible to anticipate and expose human operators to all possible situations that could be encountered. Therefore, an interesting prospect is to consider indirect training or “cognitive training” that is dedicated to enhancing executive functioning, thus improving the ability to deal with complex situations. Indeed, WM and mental flexibility are abilities that have shown to be good predictors of the trend to persist or not in erroneous decision making (Causse, Dehais, & Pastor, 2011), and so enhancement of these functions should lead to better performance. The underlying approach – defined in the field of Neuropsychology and Neuro-rehabilitation – consists of recurrent training sessions using a battery of cognitive tests. This method has demonstrated its efficiency in enhancing a broad set of executive functions in healthy participants, with particular involvment of the prefrontal cortex

(Packwood, Hodgetts, & Tremblay, 2011). For instance, WM performance has been shown to improve after five weeks of training and this was associated with anatomical changes (Dahlin, Neely, Larsson, Backman, & Nyberg, 2008). Furthermore, improvements in mental flexibility have been obtained by transfer learning via the training of executive functions using a multitasking paradigm (Anguera et al., 2013).

A recent trend in cognitive training consists of the integration of a neurostimulation tool such as transcranial direct current stimulation (tDCS) and high definition tDCS (HD-tDCS) during cognitive training sessions to boost executive functionning (see Callan, Falcone, Wada, & Parasuraman, 2016). Initially used for clinical purposes, some studies have demonstrated that the use of tDCS over prefrontal sites can enhance such abilities as attention and performance on vigilance and threat detection tasks (Falcone, Coffman, Clark, & Parasuraman, 2012; Parasuraman & Galster, 2013), as well as WM (Fregni et al., 2005). One benefit of this technique is that it is portable and can be combined with other brain imaging techniques under real life situations (McKendrick, Parasuraman, & Ayaz, 2015, Gateau, Ayaz, & Dehais, 2018), opening the possibility for real-time neuro-modulation of cerebral activity. For instance, two studies have shown that stimulation over DLPFC sites could improve set shifting skills (Leite et al 2011, Jeon et Han, 2012, see Tremblay, et al., 2014, for a review), demonstrating that this technique might have some potential to mitigate perseveration. However, these results should be taken with caution: given the complexity of the multifactorial design (e.g., sham vs anodal vs cathodal stimulation; left vs right DLPFC stimulation; type of task), the sample size (n~30) of these two off-line stimulation studies could be considered rather small and potentially problematic given that the efficiency of tDCS is highly subject to inter individuals' responses (Tremblay et al., 2014). A further limitation is that follow up tests to investigate the very long-term efficiency of neurostimulation on executive functioning were not conducted. Moreover, ethical concerns regarding this technique, especially with healthy subjects, means that further research and caution over use are essential.

Alternatively, the use of medication is a way to improve executive functionning. For instance, Yesavage et al. (2002) administered dopenezil, an inhibitor of acetylcholinesterase, that is currently used in the treatment of Alzeihmer patients. After thirty days of treatment, subtle but significant improvement was found in pilots' ability to retain complex procedures and to deal with unexpected critical situations in a flight simulator. Aside from the potential side effects of such drug, this result raises very strong ethical and practical questions about its use to improve performance within healthy participants. Thus, a more reasonable approach is to consider meditation techniques that have been proven to enhance cognitive performance and well-being (Moore, & Malinowski, 2009). For instance, these authors found that mindfulness meditation improved cognitive flexibility, suggesting that this technique could be promising to prevent the occurrence of perseveration in humans operating critical systems.

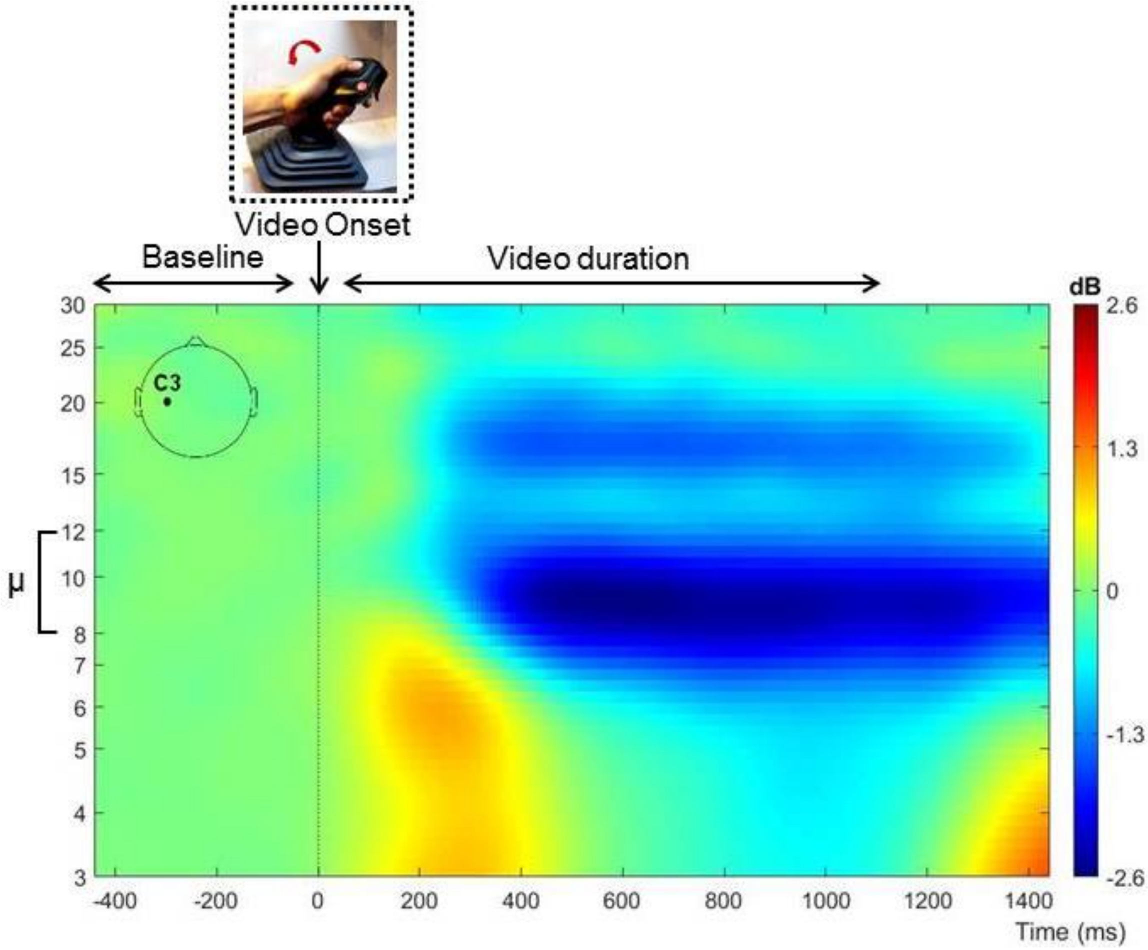
As previously discussed, perseveration may result not just from an executive deficit (i.e. compromised DLPCF activity) but also from a failure of attention. Thus, perseverative error at an attentional level presents interface designers with a paradox: how can one expect to "cure" human operators from such behavior if the warning designed to alert them is neglected? For instance, human factors experiments have shown that the absence of response to either auditory (Dehais et al., 2012) or visual alarms (Dehais, Causse, & Tremblay, 2011) may be explained by an inability to disengage attention. These studies tend to show that the classical approach that consists of adding more information (e.g. flashing light, aural alarm) to warn human operators often fails to disengage and capture attention under stressful settings.

Therefore, one solution could consist of temporarily removing the information on which the human operator is focused, and instead replacing it with an explicit stimulus in the visual field. The user interface thus acts as a cognitive prosthesis to perform the attentional disengagement and attentional shifting (Dehais et al., 2012). The rationale is also to reduce the amount of information and cascades of alarms that generally occur during critical incidents and that have shown to be counter-productive. This principle was successfully tested with pilots in a flight simulator (Dehais, Tessier, & Chaudron, 2003) and in the context of human-unmanned vehicle interaction (Dehais et al., 2013). However, given the effect that a temporary removal of task-related information could have on the ongoing task, such countermeasures may not be appropriate for all contexts and should only be considered in cases in which strategy change is imperative, and not simply as another form of alert (Imbert, Hodgetts, Pariseé, Vachon, Dehais, & Tremblay, 2014).

Another possible solution is to reduce the time and the complexity of the cortical processing of alarms. One must understand that responding to a warning involves a multi-step process: perceiving, paying attention, understanding, evaluating validity, and then elaborating and initiating the appropriate motor response. One original approach is to consider techniques such as those relying on mirror neurons that have been successfully used for patients' rehabilitation (Rizzolatti, Fabbri-Destro, & Cattaneo, 2009). Firstly, discovered in monkeys, the mirror motor neurons (Rizzolatti & Craighero, 2004) are known to fire both during observation and performance of an action. Electrophysiological studies have emphasized that observing an action modifies electrical activity within the sensorimotor cortices (Gastaut & Bert, 1954). More specifically mu EEG rhythm, ranging from 8Hz to 13 Hz, is attenuated when participants perform an action or when they simply watch moving pictures of the same actions.

These mirror neurons are thought to be important in action understanding and have been shown to play a key role in flying (Callan et al., 2012). One candidate solution may be utilizing the user interface to inform the pilot of the necessary action to perform, even if this is subject to inattentional deafness or deleterious high stress. By displaying an intuitive video showing the urgent motor action to be performed (e.g., pulling the stick), a preliminary study indicated that the response time to actually activate the motor cortex and perform the action could be halved (Causse, Phan, Ségonzac, & Dehais, 2012), due to the solicitation of mirror neurons (see Figure 6). Similarly, simply hearing sounds of actions might also help initiate the required motor actions by activating mirror neurons, as shown in monkeys (Kohler et al., 2002).

Figure 6 about here



However, it should be noted that perseverative behaviors can be either unconscious and involontary, whereby the operator is caught in the wrong strategy – as is the case with attentional limitations and executive lapses – or they can be conscious and voluntary, in the form of risk taking, whereby the operator makes erroneous decisions in a conscious and lucid state. Studies carried out to date show that cognitive countermeasures are effective in mitigating the effects of unconscious perseveration (Dehais, Causse, & Tremblay, 2011) by redirecting attention to priority information. On the other hand, operators who have all their cognitive abilities but who are overly confident and consciously decide to pursue the original course of action, will probably deliberately ignore whatever cognitive countermeasures are implemented to try to invoke a strategy change. Ultimately, approaches that leave the level of system autonomy intact and do not provide adaptive automation will all be limited by the final (conscious) decision of the operator.

Conclusions

The current article combines human factors and neuroscience knowledge to present the idea of a cognitive continuum as a means to understanding and mitigating perseveration in complex and dynamic occupational settings. In particular, we raise the question as to why highly trained individuals continue to persist with non-adaptive and irrational courses of action, even when provided with information that should instigate a change in strategy. With neuroimaging techniques such as fNIRS, EEG, and fMRI, it is possible to complement subjective assessments and purely observable behaviors, to instead gain insight into the changes occurring at a neuronal level when ill-judged decisions/strategies continue to be pursued. Neuroimaging techniques show that measurable changes in brain functioning do indeed occur when an individual experiences non-adaptive behaviors. We introduce the idea that seemingly irrational behavior displayed by individuals in particularly pressurized or complex situations could perhaps be attributed to a momentary “malfunction” of brain processes (particularly executive processes), whereby high levels of stress or workload can render the healthy brain temporarily impaired.

Although executive functioning lacks a formal definition – indeed a recent literature review identified a total of 68 executive subcomponents (Packwood, Hodgetts, & Tremblay, 2011) – it could be broadly described as the higher order control processes that direct and coordinate behavior in an adaptive manner. Clinical patients that exhibit executive deficits typically have damage to the frontal lobe, and display difficulty in areas such as problem solving, inhibition, and task switching. Executive functioning is also intrinsic to the human factors domain since complex, multitasking, and safety-critical work environments (such as aviation, emergency response, military operations) are characterized by dynamic decision making. This process alone is likely to subsume a number of proposed executive functions (e.g., cognitive flexibility, monitoring, motor planning, shifting attention, managing multiple goals). At an observable, behavioral level, similarities have been highlighted between the types of behavior exhibited by patients with DLPFC lesions, and those displayed by personnel operating in dynamic and pressurized decision-making environments (e.g., updating goals, inhibiting irrelevant goals, planning alternative goals, evaluating goal values). The cognitive continuum hypothesis makes the novel suggestion that healthy adults can sometimes experience a temporary breakdown in cognitive function, akin to that of clinical patients, when acting or making decisions under extreme critical situations.

Following this approach, we have also shown that attentional control is critical to ensure adaptive behaviors in a real-life multimodal environment. The adequate orientation of attention towards the most relevant items encompasses a brain network including temporal, parietal, and PFC/DLPFC cortices. The review of brain imaging studies demonstrates that the superior temporal and parietal cortices are thought to act as circuit breakers to shut down early sensory structures, thus potentially preventing the processing of novel and relevant stimuli. As for executive control, DLPFC seems to play a key role for attentional control by maintaining the relevant pre-processed information in

WM (see Curtis, &Esposito, 2004) and allowing selection of the most relevant information with regards to the on-going task (Johnson, Strafella, Zatorre, 2007; Johnson, & Zatorre, 2006). As a consequence, its transient impairment compromises the ability to switch attention toward new stimuli that could invoke a change in behavior.

Taken together, these findings suggest that the DLPFC is at the interface between executive and attentional control, and that its transient (stressors, neurostimulation) or permanent (lesion) impairment is detrimental to exhibiting adaptive behavior. Finally, viewing DLPFC deficits – whether permanent, or temporary and circumstantial – as deriving from the same malfunction of neural mechanisms opens up the possibility to apply potential solutions from neuropsychology to human factors ranging from direct and indirect training, meditation, neurostimulation of the DLPFC, and cognitive countermeasures.

Acknowledgements

The research conducted by the authors and reported in this review is supported by the AXA Research Fund through the Neuroergonomics For Safety Chair to Frédéric Dehais, by the Natural Sciences and Engineering Research Council of Canada - Discovery grant awarded to Sébastien Tremblay - and by the foundation ISAE-SUPAERO. Thanks are due to Dr Francois Vachon, Emilie Jahanpour, and also to Mark Parent for their contribution to some of the empirical work reported in the paper.

References

Anderson, S. W., Damasio, H., Jones, R. D., & Tranel, D. (1991). Wisconsin Card Sorting Test performance as a measure of frontal lobe damage. *Journal of Clinical and Experimental Neuropsychology*, *13*, 909–922. https://doi.org/10.1080/01688639108405107

Anguera, J. A., Boccanfuso, J., Rintoul, J. L., Al-Hashimi, O., Faraji, F., Janowich, J., Kong, E., Larraburo, Y., Rolle, C., Johnston, E., & Gazzaley, A. (2013). Video game training enhances cognitive control in older adults. *Nature*, *501*, 97–101.

Arnsten, A. F. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews Neuroscience*, *10,* 410 - 422.

Atkinson, J. W., & Cartwright, D. (1964). Some neglected variables in contemporary conceptions of decision and performance. Monograph Supplement 5-V14. *Psychological Reports*, *14*, 575–590.

Barkley, R. A. (2001). The Executive Functions and Self-Regulation: An Evolutionary Neuropsychological Perspective. *Neuropsychology Review*, *11*, 1–29. https://doi.org/10.1023/A:1009085417776

Beauchamp, M. S., Lee, K. E., Argall, B. D., & Martin, A. (2004). Integration of auditory and visual information about objects in superior temporal sulcus. *Neuron*, *41*(5), 809-823.

Beck, D. M., Rees, G., Frith, C. D., & Lavie, N. (2001). Neural correlates of change detection and change blindness. *Nature neuroscience*, *4*(6), 645.

Berg, E. A. (1948). A simple objective technique for measuring flexibility in thinking. *The Journal of General Psychology*, *39*, 15.

Bliss, J. P. (2003). Investigation of alarm-related accidents and incidents in aviation. *The International Journal of Aviation Psychology*, *13*(3), 249–268.

Bliss, J. P., & Dunn, M. C. (2000). Behavioural implications of alarm mistrust as a function of task workload. *Ergonomics*, *43*(9), 1283–1300.

Braboszcz, C., & Delorme, A. (2011). Lost in thoughts: neural markers of low alertness during mind wandering. *Neuroimage*, *54*(4), 3040–3047.

Breznitz, S. (2013). *Cry wolf: The psychology of false alarms*. Psychology Press.

Bromiley, M. (2008). Have you ever made a mistake. *RCoA Bulletin*, *48*, 2442-5.

Brown, J. C., & Anglin-Regal, P. (2008). Clinical alarm management: a team effort. *Biomedical Instrumentation & Technology*, *42*(2), 142–144.

Bureau d'Enquêtes et d'Analyses (BEA). (2012). Final Report On the accident on 1st June 2009 to the Airbus A330-203 registered F-GZCP operated by Air France flight AF 447 Rio de Janeiro – Paris. http://www.bea.aero/docspa/2009/f-cp090601.en/pdf/f-cp090601.en.pdf

Burian, B., Orasanu, J., & Hitt, J. (2000). Weather-related decision errors: Differences across flight types. *Proceedings of the 14th Triennial Congress of the International Ergonomics Association/44th Annual Meeting of the Human Factors and Ergonomics Society* (22–25). Santa Monica, CA: HFES.

Callan, D. E., Falcone, B., Wada, A., & Parasuraman, R. (2016). Simultaneous tDCS-fMRI identifies resting state networks correlated with visual search enhancement. *Frontiers in Human Neuroscience*, *10*: 72.

Callan, D. E., Gamez, M., Cassel, D. B., Terzibas, C., Callan, A., Kawato, M., & Sato, M. A. (2012). Dynamic visuomotor transformation involved with remote flying of a plane utilizes the 'Mirror Neuron'system. PloS one, 7(4), e33873.

Callan, D. E., Gateau, T., Durantin, G., Gonthier, N., & Dehais, F. (2018). Disruption in neural phase synchrony is related to identification of inattentional deafness in real‐world setting. *Human Brain Mapping*. 39(6), 2596-2608.

Casner, S. M., & Schooler, J. W. (2015). Vigilance impossible: Diligence, distraction, and daydreaming all lead to failures in a practical monitoring task. *Consciousness and Cognition*, *35*, 33–41.

Causse, M., Dehais, F., Arexis, M., & Pastor, J. (2011). Cognitive aging and flight performances in general aviation pilots. *Aging, Neuropsychology, and Cognition*, *18*(5), 544–561.

Causse, M., Dehais, F., & Pastor, J. (2010). Flight experience and executive functions predict flight simulator performance in general aviation pilots. *Proceedings of the International Conference for Research in Air Transportation.*

Causse, M., Dehais, F., & Pastor, J. (2011). Executive functions and pilot characteristics predict flight simulator performance in general aviation pilots. *The International Journal of Aviation Psychology*, *21*, 217 -234.

Causse, M., Imbert, J.-P., Giraudet, L., Jouffrais, C., & Tremblay, S. (2016). The role of cognitive and perceptual loads in inattentional deafness. *Frontiers in Human Neuroscience*, *10*: 344.

Causse, M., Péran, P., Dehais, F., Caravasso, C., Zeffiro, T., Sabatini, U., & Pastor, J. (2013). Affective decision making under uncertainty during a plausible aviation task: an fMRI study. *NeuroImage*, *71*, 19 - 29.

Causse, M., Phan, J., Ségonzac, T., & Dehais, F. (2012). Mirror Neuron Based Alerts for Control Flight Into Terrain Avoidance. *Advances in Cognitive Engineering and Neuroergonomics*, *16*, 157 - 166.

Chabris, C. F., Weinberger, A., Fontaine, M., & Simons, D. J. (2011). You do not talk about Fight Club if you do not notice Fight Club: Inattentional blindness for a simulated real-world assault. *i-Perception*, *2*(2), 150-153.

Chamberland, C., Hodgetts, H.M., Vallières, B., Vachon, F., & Tremblay, S. (2017). The benefits and the costs of exploiting the auditory modality in dynamic decision-making settings. *Journal of Cognitive Engineering and Decision Making.* Manuscript provisionally accepted for publication.

Chang, C. F., Hsu, T. Y., Tseng, P., Liang, W. K., Tzeng, O. J., Hung, D. L., & Juan, C. H. (2013). Right temporoparietal junction and attentional reorienting. *Human Brain Mapping*, *34*(4), 869-877.

Cho, K., Ennaceur, A., Cole, J. C., & Suh, C. K. (2000). Chronic jet lag produces cognitive deficits. *The Journal of Neuroscience*, *20*(6), RC66.

Clancy, F., Prestwich, A., Caperon, L., & O'Connor, D. B. (2016). Perseverative cognition and health behaviors: A systematic review and meta-analysis. Frontiers in human neuroscience, 10, 534.

Collyer, S. C., & Malecki, G. S. (1998). Tactical decision making under stress: History and overview. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress: Implications for individual and team training* (3–15). Washington, DC: American Psychological Association.

Collins, A. & Koechlin, E. (2012). Reasoning, Learning, and Creativity: Frontal lobe function and human decision-making, *Plos Biology* 10(3): e1001293.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. Nature reviews neuroscience, 3(3), 201.

Corbetta, M., & Shulman, G. L. (2011). Spatial neglect and attention networks. *Annual review of neuroscience*, *34*, 569-599.

Cowen, E. L. (1952). The influence of varying degrees of psychological stress on problem-solving rigidity. The Journal of Abnormal and Social Psychology, 47(2S), 512.

Dahlin, E., Neely, A. S., Larsson, A., Bäckman, L., & Nyberg, L. (2008). Transfer of learning after updating training mediated by the striatum. *Science*, *320*, 1510–1512.

Dehais, F., Causse, M., Régis, N., Menant, E., Labedan, P., Vachon, F., & Tremblay, S. (2012). Missing Critical Auditory Alarms in Aeronautics: Evidence for Inattentional Deafness? *Proceedings of the 56th Human Factors and Ergonomics Society Annual Meeting*, (1639–1643). Santa Monica, CA: HFES.

Dehais, F., Causse, M., & Tremblay, S. (2011). Mitigation of Conflicts with Automation Use of Cognitive Countermeasures. *Human Factors*, *53*, 448–460.

Dehais, F., Causse, M., Vachon, F., Régis, N., Menant, E., & Tremblay, S. (2014). Failure to Detect Critical Auditory Alerts in the Cockpit Evidence for Inattentional Deafness. *Human Factors, 56*, 631-44.

Dehais, F., Causse, M., Vachon, F., & Tremblay, S. (2012). Cognitive conflict in human–automation interactions: A psychophysiological study. *Applied Ergonomics, 43,* 588-595.

Dehais, F., Roy, R. N., Durantin, G., Gateau, T., & Callan, D. (2017). EEG-Engagement Index and Auditory Alarm Misperception: An Inattentional Deafness Study in Actual Flight Condition. *In International Conference on Applied Human Factors and Ergonomics* (227-234). Springer, Cham.

Dehais, F., Roy, R. N., & Scannella, S. (2019). Inattentional deafness to auditory alarms: Inter-individual differences, electrophysiological signature and single trial classification. Behavioural brain research, 360, 51-59.

Dehais, F., Tessier, C., & Chaudron, L. (2003). GHOST: experimenting conflicts countermeasures in the pilot's activity. *Proceedings of the International Joint Conference on Artificial Intelligence (IJCAI)*, *18*, 163–168.

Delgado, M. R., Gillis, M. M. & Phelps, E. A. (2008). Regulating the expectation of reward via cognitive strategies. *Nature Neuroscience*, 11, 880-881.

Del Giorno, J. M., Hall, E. E., O'Leary, K. C., Bixby, W. R., & Miller, P. C. (2010). Cognitive function during acute exercise: a test of the transient hypofrontality theory. *Journal of Sport and Exercise Psychology, 32*, 312-323.

Dekker, S. W. (2005). Past the edge of chaos. *Human Factors and Aerospace Safety*, 6, 235 - 246.

Dietrich, A. (2003). Functional neuroanatomy of altered states of consciousness: the transient hypofrontality hypothesis. *Consciousness and cognition, 12,* 231–256.

Dolan, R. J. (2002). Emotion, cognition, and behavior. *Science*, *298*, 1191–1194.

Dolcos, F., & McCarthy, G. (2006). Brain systems mediating cognitive interference by emotional distraction. *The Journal of Neuroscience*, *26*(7), 2072–2079.

Donoso, M., Collins, A. G., & Koechlin, E. (2014). Foundations of human reasoning in the prefrontal cortex. *Science*, *344*, 1481–1486.

Dreisbach, G., & Goschke, T. (2004). How positive affect modulates cognitive control: reduced perseveration at the cost of increased distractibility. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*(2), 343 - 353.

Drew, T., Võ, M. L. H., & Wolfe, J. M. (2013). The invisible gorilla strikes again: Sustained inattentional blindness in expert observers. Psychological science, 24(9), 1848-1853.

Durantin, G., Dehais, F., & Delorme, A. (2015). Characterization of mind wandering using fNIRS. *Frontiers in Systems Neuroscience*, *9*: 45.

Durantin, G., Dehais, F., Gonthier, N., Terzibas, C., & Callan, D. E. (2017). Neural signature of inattentional deafness. *Human Brain Mapping*. Durantin, G., Gagnon, J.-F., Tremblay, S., & Dehais, F. (2014). Using near infrared spectroscopy and heart rate variability to detect mental overload. *Behavioural Brain Research*, *259*, 16–23.

Durantin, G., Scannella, S., Gateau, T., Delorme, A., & Dehais, F. (2015). Processing Functional Near Infrared Spectroscopy Signal with a Kalman Filter to Assess

Working Memory during Simulated Flight. *Frontiers in Human Neuroscience*, *9*: 707.

Edworthy, J. (2013). Alarms are still a problem! *Anaesthesia*, 68(8), 791-794.

Ellenbogen, M. A., Schwartzman, A. E., Stewart, J., & Walker, C. D. (2006). Automatic and effortful emotional information processing regulates different aspects of the stress response. *Psychoneuroendocrinology, 31*, 373-387.

Fecteau, S., Pascual-Leone, A., Zald, D. H., Liguori, P., Théoret, H., Boggio, P. S., & Fregni, F. (2007). Activation of prefrontal cortex by transcranial direct current stimulation reduces appetite for risk during ambiguous decision making. *Journal of Neuroscience*, *27*(23), 6212–6218.

Fioratou, E., Flin, R., & Glavin, R. (2010). No simple fix for fixation errors: cognitive processes and their clinical applications. *Anaesthesia*, *65*(1), 61–69.

Fox, S., & Hoffman, M. (2002). Escalation behavior as a specific case of goal-directed activity: A persistence paradigm. *Basic and Applied Social Psychology*, *24*(4), 273–285.

Fox, MD, Snyder, AZ, Vincent JL, Corbetta, M, Essen, D.C. , & Raichle, E.M. (2005) The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences of the United States of America*. 102:9673–9678.

Fenoy, A. J., Severson, M. A., Volkov, I. O., Brugge, J. F., & Howard, M. A. (2006). Hearing suppression induced by electrical stimulation of human auditory cortex. *Brain research*, 1118(1), 75-83.

Fregni, F., Boggio, P. S., Nitsche, M., Bermpohl, F., Antal, A., Feredoes, E., … Paulus, W. (2005). Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. *Experimental Brain Research*, *166*(1), 23–30.

Friedrich, F. J., Egly, R., Rafal, R. D., & Beck, D. (1998). Spatial attention deficits in humans: a comparison of superior parietal and temporal-parietal junction lesions. *Neuropsychology*, *12*(2), 193.

Fuster, J. M. (1988). *Prefrontal cortex: Anatomy, Physiology, and Neuropsychology of the Frontal Lobe*. New York: Raven Press.

Gaba, D. M. (1989). Human error in anesthetic mishaps. *International Anesthesiology Clinics*, *27*(3), 137–147.

Galéra, C., Orriols, L., M'Bailara, K., Laborey, M., Contrand, B., Ribéreau-Gayon, R., … Fort, A. (2012). Mind wandering and driving: responsibility case-control study. *British Medical Journal*, *345*, e8105.

Gateau, T., Ayaz, H., & 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. *Frontiers in human neuroscience*, 12, 187.

Gibb, R., & Gray, R. (2016). *Aviation visual perception: Research, misperception and mishaps*. Routledge.

Goll, J. C., Crutch, S. J., & Warren, J. D. (2010). Central auditory disorders: toward a neuropsychology of auditory objects. *Current opinion in neurology*, *23*(6), 617.

Gross, J. (1998), Antecedent- Response-Focused Emotion Regulation: Diverse Consequences for Experience, Expression, and Physiology. *Journal of Personality and Social Psychology*, 74(1), 224-237.

Haigh, M. S., & List, J. A. (2005). Do professional traders exhibit myopic loss aversion? An experimental analysis. *The Journal of Finance*, *60*(1), 523–534.

Hall, R. E., Fragola, J. & Wreathall, J. (1982). Post event human decision errors: Operator action tree / time reliability correlation (NUREG/CR-3010). Washington, DC: U. S. Nuclear Regulatory Commission.

Hare, T., Camerer, C. & Rangel, A. (2009). Self-control in decision making involves modulation of the vMPFC valuation system. *Science*, 324, 646-648.

Harrivel, A. R., Weissman, D. H., Noll, D. C., & Peltier, S. J. (2013). Monitoring attentional state with fNIRS. *Frontiers in Human Neuroscience*, *7*: 861.

Hauser, M. D. (1999). Perseveration, inhibition and the prefrontal cortex: a new look. Current opinion in neurobiology, 9(2), 214-222.

He, B. J., Snyder, A. Z., Vincent, J. L., Epstein, A., Shulman, G. L., & Corbetta, M. (2007). Breakdown of functional connectivity in frontoparietal networks underlies behavioral deficits in spatial neglect. *Neuron*, *53*(6), 905-918.

Head, D., Kennedy, K. M., Rodrigue, K. M., & Raz, N. (2009). Age differences in perseveration: Cognitive and neuroanatomical mediators of performance on the Wisconsin Card Sorting Test. *Neuropsychologia*, *47*, 1200–1203.

Ho, A. M. H., Leung, J. Y., Mizubuti, G. B., Contardi, L. H., Chan, M. T., Lo, T. S., & Lee, A. K. (2017). Inattentional blindness in anesthesiology: A simulation study. Journal of Clinical Anesthesia, 42, 36-39.

Hodgetts, H.M., Farmer, E.W., Joose, M., Parmentier, F., Schaefer, D., Hoogeboom, P., van Gool., M., & Jones, D.M. (2005). The effects of party line communication on flight task performance. In D. de Waard, K. Brookhuis, R. van Egmond, and T.

Boersema (Eds.), *Human Factors in Design, Safety, and Management,* (327 – 338). Maastricht, Netherlands: Shaker publishing.

Hodgetts, H.M., Vachon, F., Chamberland, C., & Tremblay, S., (2017). See no Evil: Challenges of security surveillance and monitoring. *Journal of Applied Research in Memory and Cognition.* Manuscript in press.

Hodgetts, H.M., Vachon, F., & Tremblay, S. (2014). Background sound impairs interruption recovery in dynamic tasks: Procedural conflict? *Applied Cognitive Psychology*, *28,* 10 – 21.

Hotz, G., & Helm-Estabrooks, N. (1995). Perseveration. Part I: a review. Brain Injury, 9(2), 151-159.

Houdé, O. (2000). Inhibition and cognitive development: Object, number, categorization, and reasoning. *Cognitive Development*, *15*(1), 63–73.

Houdé, O., Zago, L., Mellet, E., Moutier, S., & Pineau, A. (2000). and Tzourio-Mazoyer, N. Shifting from the perceptual brain to the logical brain: The neural impact of cognitive inhibition training. *Journal of Cognitive Neuroscience*, *12*, 721–728.

Imbert, J.-P., Hodgetts, H. M., Pariseé, PR., Vachon, F., Dehais, F., & Tremblay, S. (2014). Attentional costs and failures in air traffic control notifications. *Ergonomics, 57,* 1817-1832.

Jeon, S. Y., & Han, S. J. (2012). Improvement of the working memory and naming by transcranial direct current stimulation. *Annals of rehabilitation medicine*, *36*(5), 585-595.

Johnson, J. A., Strafella, A. P., & Zatorre, R. J. (2007). The role of the dorsolateral prefrontal cortex in bimodal divided attention: two transcranial magnetic stimulation studies. *Journal of Cognitive Neuroscience*, *19*(6), 907-920.

Johnson, J. A., & Zatorre, R. J. (2006). Neural substrates for dividing and focusing attention between simultaneous auditory and visual events. *Neuroimage*, *31*(4), 1673–1681.

Kennedy, K., & Raz, N. (2009). Aging white matter and cognition: differential effects of regional variations in diffusion properties on memory, executive functions, and speed. *Neuropsychologia*, *47*, 916–927.

De Keyser, V., & Woods, D. D. (1990). Fixation errors: failures to revise situation assessment in dynamic and risky systems. In S*ystems reliability assessment* (231-251). Springer Netherlands.

Knoch, D., Gianotti, L. R., Pascual-Leone, A., Treyer, V., Regard, M., Hohmann, M., & Brugger, P. (2006). Disruption of right prefrontal cortex by low-frequency repetitive transcranial magnetic stimulation induces risk-taking behavior. *Journal of Neuroscience*, *26*(24), 6469–6472.

Kohler, E., Keysers, C., Umiltà, M. A., Fogassi, L., Gallese, V., & Rizzolatti, G. (2002). Hearing Sounds, Understanding Actions: Action Representation in Mirror Neurons. *Science*, *297*, 846 - 848. https://doi.org/10.1126/science.1070311

Kozuch, B. (2014). Prefrontal lesion evidence against higher-order theories of consciousness. *Philosophical Studies*, *167*(3), 721-746.

Knight, R. T., Scabini, D., Woods, D. L., & Clayworth, C. (1988). The effects of lesions of superior temporal gyrus and inferior parietal lobe on temporal and vertex components of the human AEP. *Electroencephalography and clinical Neurophysiology*, *70*(6), 499-509.

Krakauer, J. (1997). *Into thin air: A personal account of the Mount Everest disaster*. Anchor books, New York.

Lanagan-Leitzel, L. K., Skow, E., & Moore, C. M. (2015). Great expectations: Perceptual challenges of visual surveillance in lifeguarding. *Applied Cognitive Psychology, 29,* 425-435.

Lavie, N., Beck, D. M., & Konstantinou, N. (2014). Blinded by the load: attention, awareness and the role of perceptual load. *Philosophical Transactions of the Royal Society B*, *369*, 20130205.

Lee, J. D. (2014). Dynamics of Driver Distraction: The process of engaging and disengaging. *Annals of Advances in Automotive Medicine*, *58*, 24 - 32.

Leite, J., Carvalho, S., Fregni, F., & Gonçalves, O. F. (2011). Task-specific effects of tDCS-induced cortical excitability changes on cognitive and motor sequence set shifting performance. *PloS one*, *6*(9), e24140.

Lemercier, C., Pêcher, C., Berthié, G., Valéry, B., Vidal, V., Paubel, P. V., Cours, M., Fort, A., Galéra, C., Gabaude, C. , Lagarde, E., & Maury, B. (2014). Inattention behind the wheel: How factual internal thoughts impact attentional control while driving. *Safety science*, 62, 279-285.

Lie, C.-H., Specht, K., Marshall, J. C., & Fink, G. R. (2006). Using fMRI to decompose the neural processes underlying the Wisconsin Card Sorting Test. *NeuroImage*, *30*(3), 1038–1049. https://doi.org/10.1016/j.neuroimage.2005.10.031

Lombardi, W., Andreason, P., Sirocco, K., Rio, D., Gross, R. E., Umhau, J. C., et al. (1999). Wisconsin Card Sorting Test: Performance following head injury: Dorsolateral fronto-striatal circuit activity predicts perseveration. *Journal of Clinical and Experimental Neuropsychology, 21,* 2–16.

Macdonald, J. S., & Lavie, N. (2011). Visual perceptual load induces inattentional deafness. *Attention, Perception, & Psychophysics*, *73*(6), 1780–1789.

Marois R, Yi DJ, Chun MM. The neural fate of consciously perceived and missed events in the attentional blink. *Neuron*. 2004;41:465–472.

Masicampo, E. J., & Baumeister, R. F. (2011). Consider it done! Plan making can eliminate the cognitive effects of unfulfilled goals. *Journal of Personality and Social Psychology*, *101*(4), 667 - 683.

Meister, I. G., Wienemann, M., Buelte, D., Grünewald, C., Sparing, R., Dambeck, N., & Boroojerdi, B. (2006). Hemiextinction induced by transcranial magnetic stimulation over the right temporo-parietal junction. *Neuroscience*, *142*(1), 119-123.

McKendrick, R., Parasuraman, R., & Ayaz, H. (2015). Wearable functional near infrared spectroscopy (fNIRS) and transcranial direct current stimulation (tDCS): expanding vistas for neurocognitive augmentation. *Frontiers in Systems Neuroscience*, *9*, 27.

Mohr, P., Biele, G. & Heekeren, H. (2010). Neural Processing of Risk. *The Journal of Neuroscience.*30(19), 6613-6619.

Molloy, K., Griffiths, T. D., Chait, M., & Lavie, N. (2015). Inattentional deafness: visual load leads to time-specific suppression of auditory evoked responses. *Journal of Neuroscience*, *35*(49), 16046–16054.

Moore, A., & Malinowski, P. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and cognition*, *18*(1), 176-186.

Murphy, S., & Dalton, P. (2016). Out of touch? Visual load induces inattentional numbness. *Journal of experimental psychology: Human Perception and Performance*, *42*(6), 761.

Nagahama, Y., Okina, T., Suzuki, N., Nabatame, H., & Matsuda, M. (2005). The cerebral correlates of different types of perseveration in the Wisconsin Card Sorting Test. *Journal of Neurology, Neurosurgery, & Psychiatry, 76*, 169 - 175.

National Transportation Safety Board (NTSB) (1979). *Aircraft Accident Report. United Airlines, Inc., McDonnell-Douglas DC-8-61, N8082U. Portland, Oregon, December 28, 1978.* NTSB-AAR-79-7. Washington, DC: NTSB.

Nikolic, M. I., Orr, J. M., & Sarter, N. B. (2004). Why pilots miss the green box: How display context undermines attention capture. *The International Journal of Aviation Psychology*, 14(1), 39-52.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. *Consciousness and Self-Regulation*, *4*, 1–18.

Ochsner, K. N. & Gross, J. (2005). The cognitive control of emotion. *Trends Cognitive Sciences*, 9, 242-249.

O'Hare, D., & Smitheram, T. (1995). Pressing On Into Deteriorating Conditions: An Application of Behavioral Decision Theory to Pilot Decision Making. *The International Journal of Aviation Psychology*, *5*, 351–370.

Orasanu, J., Martin, L., & Davison, J. (2001). Cognitive and Contextual Factors in Aviation Accidents: Decision Errors. In E. Salas and G.A. Klein. *Linking Expertise and Naturalistic Decision making* (209–225). Mahwah, NJ: Lawrence Erlbaum Associates.

Orzeł-Gryglewska Jolanta. (2010). Consequences of sleep deprivation. *International Journal of Occupational Medicine and Environmental Health*, *23*(1), 95 - 114.

Packwood, S., Hodgetts, H. M., & Tremblay, S. (2011). A multi-perspective approach to the conceptualization of Executive Functions. *Journal of Clinical and Experimental Neuropsychology, 33(4),* 456-470.

Pastor, J. (1999). *Reasoning and the underlying cerebral mechanisms : an Artificial Intelligence Approach*. Rennes 1 University.

Penfield, W., & Rasmussen, T. (1950). The cerebral cortex of man: a clinical study of localization of function. MacMillan

Pessoa, L., & Ungerleider, L. G. (2004). Neural correlates of change detection and change blindness in a working memory task. Cerebral Cortex, 14(5), 511-520.

Petersen, R. C. (2004). Mild cognitive impairment as a diagnostic entity. *Journal of Internal Medicine*, *256*(3), 183–194.

Rauss, K. S., Pourtois, G., Vuilleumier, P., & Schwartz, S. (2009). Attentional load modifies early activity in human primary visual cortex. *Human Brain Mapping*, *30*(5), 1723–1733.

Raveh, D., & Lavie, N. (2015). Load-induced inattentional deafness. *Attention, Perception, & Psychophysics*, *77*(2), 483–492.

Rees, G. (2001). Neuroimaging of visual awareness in patients and normal subjects. *Current opinion in neurobiology*, *11*(2), 150-156.

Ridderinkhof, K. R., Span, M. M., & van der Molen, M. W. (2002). Perseverative behavior and adaptive control in older adults: Performance monitoring, rule induction, and set shifting. *Brain and Cognition*, *49*(3), 382–401. https://doi.org/10.1006/brcg.2001.1506

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Review of Neuroscience*, *27*, 169–192.

Rizzolatti, G., Fabbri-Destro, M., & Cattaneo, L. (2009). Mirror neurons and their clinical relevance. *Nature Clinical Practice Neurology*, *5*(1), 24–34.

Robertson, I., & Halligan, P. (1999). *Spatial neglect: A clinical handbook for diagnosis and treatment*. Psychology press.

Robertson, L. C., Lamb, M. R., & Knight, R. T. (1988). Effects of lesions of temporal-parietal junction on perceptual and attentional processing in humans. *Journal of Neuroscience*, *8*(10), 3757-3769.

Rochlin, G. I. (1991). Iran Air Flight 655 and the USS Vincennes. In *Social responses to large technical systems* (99–125). Springer.

Rogers, W. P. (1986). *Report of the presidential commission on the space shuttle challenger accident*.

Rouch, I., Wild, P., Ansiau, D., & Marquié, J.-C. (2005). Shiftwork experience, age and cognitive performance. *Ergonomics*, *48*(10), 1282–1293. https://doi.org/10.1080/00140130500241670

Sandson, J., & Albert, M. L. (1984). Varieties of perseveration. *Neuropsychologia*, *22*, 715–732.

Schwid, H. A., & O’Donnell, D. (1992). Anesthesiologists’ management of simulated critical incidents. *Anesthesiology*, *76*(4), 495–501.

Shanteau, J., & Dino, G. A. (1993). Environmental stressor effects on creativity and decision making. In Time pressure and stress in human judgment and decision making (293-308). Springer, Boston, MA.

Simons, D. J., & Levin, D. T. (1997). Change blindness. *Trends in Cognitive Sciences*, *1*(7), 261–267.

Simpson, J., Drevets, W., Snyder, A., Gusnard, D., & Raichle, M. (2001). Emotion-induced changes in human medial prefrontal cortex: II. During anticipatory anxiety. *Proceedings of the National Academy of Sciences of the United States of America*, *98*, 688.

Simpson, J., Snyder, A., Gusnard, D., & Raichle, M. (2001). Emotion-induced changes in human medial prefrontal cortex: I. During cognitive task performance. *Proceedings of the National Academy of Sciences*, *98*, 683.

Smallwood, J., Beach, E., Schooler, J. W., & Handy, T. C. (2008). Going AWOL in the brain: Mind wandering reduces cortical analysis of external events. *Journal of Cognitive Neuroscience*, *20*(3), 458–469.

Sorkin, R. D. (1988). FORUM: Why are people turning off our alarms? *The Journal of the Acoustical Society of America*, *84*(3), 1107–1108.

Sörqvist P., Stenfelt S., Rönnberg J. (2012). Working memory capacity and visual-verbal cognitive load modulate auditory-sensory gating in the brainstem: Toward a unified view of attention. *Journal of Cognitive Neuroscience, 24,* 2147–2154.

Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of experimental psychology: Applied, 9(1),* 23.

Stuss, D., & Knight, R. (2013). *Principles of frontal lobe function*. OUP USA.

Suss, J., Vachon, F., Lafond, D., & Tremblay, S. (2015, August). Don't overlook the human! Applying the principles of cognitive systems engineering to the design of intelligent video surveillance systems. *In Advanced Video and Signal Based Surveillance (AVSS), 2015 12th IEEE International Conference on* (1-6). IEEE.

Tellinghuisen, D. J., Cohen, A. J., & Cooper, N. J. (2016). Now hear this: Inattentional deafness depends on task relatedness. *Attention, Perception, & Psychophysics*, *78*(8), 2527–2546.

Todd JJ, Fougnie D, Marois R. Visual short-term memory load suppresses temporo-parietal junction activity and induces inattentional blindness. Psychological Science. 2005; 16:965–972

Tombu, M. N., Asplund, C. L., Dux, P. E., Godwin, D., Martin, J. W., & Marois, R. (2011). A unified attentional bottleneck in the human brain. *Proceedings of the National Academy of Sciences*, *108*(33), 13426–13431.

Tremblay, S., Lepage, J. F., Latulipe-Loiselle, A., Fregni, F., Pascual-Leone, A., & Théoret, H. (2014). The uncertain outcome of prefrontal tDCS. *Brain stimulation*, *7*(6), 773-783.

Van der Linden, D., Frese, M., & Meijman, T. F. (2003). Mental fatigue and the control of cognitive processes: effects on perseveration and planning. *Acta Psychologica*, *113*(1), 45-65.

Waegeman, A., Declerck, C. H., Boone, C., Seurinck, R., & Parizel, P. M. (2014). Individual differences in behavioral flexibility in a probabilistic reversal learning task: An fMRI study. *Journal of Neuroscience, Psychology, and Economics*, *7*(4), 203 - 218.

Wiggins, M., & O'Hare, D. (1995). Expertise in aeronautical weather-related decision making: A cross-sectional analysis of general aviation pilots. *Journal of Experimental Psychology: Applied*, *1*, 305–320.

Yanko, M. R., & Spalek, T. M. (2014). Driving with the wandering mind: the effect that mind-wandering has on driving performance. *Human factors*, 56(2), 260-269.

Yechiam, E., & Hochman, G. (2013). Losses as modulators of attention: review and analysis of the unique effects of losses over gains. *Psychological bulletin*, *139*(2), 497.

Yesavage, J. A., Mumenthaler, M. S., Taylor, J. L., Friedman, L., O'Hara, R., Sheikh, J., Tinklenberg, P.J, & Whitehouse, P. J. (2002). Donepezil and flight simulator performance: effects on retention of complex skills. *Neurology*, *59*(1), 123-125.

Figure captions

Figure 1: Illustration of the cognitive continuum from a healthy subject with optimal performance to a patient with permanent lesions in the dorsolateral prefrontal cortex (DLPFC). The cognitive performance of a healthy but stressed subject lies between the two, exhibiting temporary low performance.

Figure 2: Illustration of the DLPFC disengagement when facing mental overload. The participants had to perform a computer-based piloting task in which they were asked to

follow a dynamic target among five aircrafts with their aircraft (middle of the screen) depending on a visual stroop-like cue. The processing load was manipulated in terms of working memory, with an N-Back-like sub-task. The combination of control difficulty and processing load allowed the creation of four levels of difficulty from easy to very hard. (a). When reaching the hardest levels of difficulty, the left-DLPFC activity is reduced (b, far right), associated with non-adaptive behavior (i.e. inability to follow the new target). Adapted from Durantin et al. (2014).

Figure 3: Neural representations of risk (a) and risk processing (b). The authors found representations of risk in bilateral anterior insula (aINS), thalamus, dorsomedial prefrontal cortex (dmPFC), right DLPFC, right parietal cortex, left precentral gyrus, and occipital cortex; they distinguish between risk processing during or before choice (decision risk) and risk processing after or without a choice (anticipation risk), with the crucial difference that risk information is likely used to guide choices in the context of decision risk but not in the context of anticipation risk. Adapted from "Neural processing of risk," by Mohr, Biele, & Heekeren, 2010, Journal of Neuroscience, 30, p. 6615, 6617.

Figure 4: Left. Correlation between the level of activity in the right DLPFC (BA9) and participants' d ' discriminability index when facing an aeronautical decision under financial pressure with high uncertainty conditions. Right. Illustration of the association between the average response in the right DLPFC region (BA9) for each participant with

their individual d' discriminability index. Risky decision makers who persisted in erroneous decision making exhibited lower DLPFC activation than safer ones.

Figure 5: Cortical regions in the Inferior Frontal Gyrus (IFG) and Superior Medial Frontal Cortex (Pre-SMA) associated with an attentional bottleneck are activated during inattentional deafness (a). Their activation is related to a decrease in functional connectivity from the IFG to the auditory processing areas (b). Adapted from Durantin et al., (2017).

Figure 6: Time frequency decomposition during rest state and the watching of the mirror neuron video. 5–30 Hz (µ) frequency bands measured on the C3 electrode (motor area) diminish (in blue) during the viewing of the video. This desynchronization of the motor neurons suggests an activation of the mirror neuron system.