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Using theta and alpha band power to assess cognitive workload in multitasking environments

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ABSTRACT

Cognitive workload is of central importance in the fields of human factors and ergonomics. A reliable measurement of cognitive workload could allow for improvements in human machine interface designs and increase safety in several domains. At present, numerous studies have used electroencephalography (EEG) to assess cognitive workload, reporting the rise in cognitive workload to be associated with increases in theta band power and decreases in alpha band power. However, results have been inconsistent with some failing to reach the required level of significance. We hypothesized that the lack of consistency could be related to individual differences in task performance and/or to the small sample sizes in most EEG studies. In the present study we used EEG to assess the increase in cognitive workload occurring in a multitasking environment while taking into account differences in performance. Twenty participants completed a task commonly used in airline pilot recruitment, which included an increasing number of concurrent sub-tasks to be processed from one to four. Subjective ratings, performances scores, pupil size and EEG signals were recorded. Results showed that increases in EEG alpha and theta band power reflected increases in the involvement of cognitive resources for the completion of one to three subtasks in a multitasking environment. These values reached a ceiling when performances dropped. Consistent differences in levels of alpha and theta band power were associated to levels of task performance: highest performance was related to lowest band power.

1. Introduction

Cognitive workload is considered as an important factor in human performance, affecting human error, system safety, productivity and operator satisfaction (Xie and Salvendy, 2000). It can be defined as "the proportion operator information processing capacity or resources that is actually required to meet system demands" (Eggemeier et al., 1991; Cain, 2007; see also Moray, 1979; Vidulich and Tsang, 2012 for reviews), the amount of cognitive resources being limited (*e.g.*, Broadbent, 1958). These cognitive resources mainly refer to attentional resources (Patten et al., 2006; Hollands and Wickens, 2000; Wickens, 1991, 2008) and to working memory capacity (Brouwer et al., 2012; Berka et al., 2007; Grimes et al., 2008) both of them representing the cognitive processes involved in cognitive workload (Sauseng et al., 2005). This concept of cognitive workload has raised many theoretical concerns (Tricot and Chanquoy, 1996), but "perhaps the most basic issue in the study of cognitive workload is the problem of how to actually measure it" (Gevins and Smith, 2003).

When assessing cognitive workload, three different measurements are usually distinguished: behavioral, subjective and physiological (Vidulich and Tsang, 2012; Cegarra and Chevalier, 2008; Kramer, 1990; Cain, 2007). They provide different information and are only rarely correlated (Funke et al., 2013), which lead to the hypothesis that these measurements reflect different aspects of the cognitive workload phenomenon (Matthews et al., 2015; Cain, 2007).

The present study focused on physiological measurements of cognitive workload, mainly using electroencephalography (EEG), however other techniques such as pupillometry might also provide valuable insight.

Pupil diameter is assumed to reflect general arousal and has also been shown to reflect variations of workload (Beatty and Lucero-Wagoner, 2000 for a review) either during laboratory experiments (Kahneman and Beatty, 1966; Peavler, 1974) or during more ecologically-valid tasks (Just and Carpenter, 1993; Ahlstrom and Friedman-Berg, 2006; Stein, 1992). Pupil size increases with cognitive effort (Kahneman et al., 1969; Iqbal et al., 2005), in response to inhibition which is assumed to consume attentional resources (Laeng et al., 2011; Chiew and Braver's, 2013) and thus also with attentional load (Lisi

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et al., 2015). However, pupil size may vary with luminosity (Beatty and Lucero-Wagoner, 2000 for a review) and with other, non-cognitive, factors, such as physical effort (Richer and Beatty, 1985). Despite these limitations, pupil size analysis remains a good indicator of cognitive load variations in laboratory experiments (Beatty and Lucero-Wagoner, 2000).

EEG is another extensively used to assess cognitive workload (Ke et al., 2014). When using EEG, it seems necessary to rely on studies that focus on the cognitive determinants of the cognitive workload, mainly attention and working memory (*e.g.*, Wickens et al., 1983). By explaining the implications of different resources, studies on cognitive determinants may help to reconcile divergent results on cognitive workload measurements. While studies of cognitive processes used laboratory settings, cognitive workload studies often used more ecologically-valid tasks. This difference might be the source of inconsistencies between the two domains. Nonetheless, explaining attention and working memory processes might help to understand variations in the measurements of cognitive workload. In the next sections, we will firstly present empirical findings of laboratory studies on EEG markers of attention and working memory. Secondly, we will present empirical findings of ecologically-valid studies on EEG cognitive workload assessments.

1.1. EEG markers of attention and working memory

Attention and working memory share parts of the same cerebral regions. However, it remains unclear whether they share the same networks and are different functions emerging from these networks or whether they rely on distinct ones (LaBar et al., 1999). Working memory is supported by prefrontal cortex and parietal areas (Sauseng et al., 2005), the left parietal lobe supporting the phonological loop (Ravizza et al., 2005) and the right parietal lobe supporting the visuo-spatial sketchpad (see d'Esposito et al., 1998 for a review, but see also LaBar et al., 1999). Activation of frontal and right parietal cerebral regions, reflected by a synchronization in the theta band (4–8 Hz) and a desynchronization in the alpha band (8–12 Hz), is sensitive to working memory load (see Schacter, 1977; Basar et al., 2001; Kahana et al., 2001; Klimesch, 1999 for review). Fronto-parietal theta power has been linked to working memory capacity in numerous studies (Sauseng et al., 2010; Klimesch, 1996), with a higher level of theta band spectral power elicited reflecting lower working memory capacity (Klimesch et al., 1999; Klimesch, 1999). These differences might be due to different amounts of cognitive resources available as well as to differences in strategies used to complete the task or perhaps an interaction between the two hypotheses (Gulbinaite et al., 2014).

In a similar manner, the solicitation of attentional resources has been linked mainly to a desynchronization of the alpha band (Klimesch, 1996; Klimesch et al., 1998) and theta band synchronization (Gevins and Smith, 2000). Both processes share the same cerebral regions and vary in the same way for numerous tasks, but alpha band synchronizations were also found during tasks soliciting frequent task switching (Pope et al., 1995). Other studies also found alpha band power to increase with task demand (Borghini et al., 2014; Kamzanova et al., 2014; Zhao et al., 2012). Recently, it was proposed that both alpha band synchronization and desynchronization might be responsible for two different working memory maintenance mechanisms (Capilla et al., 2014). As a result, alpha band synchronization would support interfering item inhibition (Rihs et al., 2007) while alpha band desynchronization would support relevant item maintenance (Fukuda et al., 2015).

1.2. EEG related workload assessment

Despite differences between laboratory settings and ecologically-valid experiments, results obtained in both fields are mostly consistent. Indeed, EEG has often been used to assess changes in mental workload and is probably the "most studied mental workload indicator" (Ke et al., 2014; Gevins et al., 1998). Considering EEG methods, an increase in workload is said to be associated with theta synchronization and with an alpha desynchronization, mainly at frontal and parietal sites (Smith et al., 1999; Antonenko, 2007).

In eliciting cognitive workload, two approaches are usually employed. The first consists in increasing the difficulty of the task, with the assumption that the more processing steps the task requires in a time unit, the higher the cognitive workload (Johannsen, 1979). The second way is to use multitasking paradigms, since the number of concurrent tasks to be processed is one of the major determinants of cognitive workload (Schvaneveldt, 1969; Yeh and Wickens, 1988; Rogers and Monsell, 1995).

1.2.1. Alpha spectral power variations

Alpha spectral band power has been shown to decrease with increased task difficulty (Sterman and Mann, 1995; Klimesch, 1999; Ota et al., 1996), as well as with increased memory load (Fairclough and Venables, 2006; Ryu and Myung, 2005; Sterman and Mann, 1995; Fairclough et al., 2005; Fournier et al., 1999; Gevins et al., 1998; Smith et al., 2001). In the same way, alpha band power decreases with the increase in experienced time pressure (Slobounov et al., 2000). This decrease in alpha brain waves is mainly located in the occipital and parietal brain locations and may be modulated by high inter-individual variations (Klimesch, 1999; Kramer, 1990). It is usually attributed to modulation due to task related attention demand, but the mere onset of the task may sometimes be sufficient to cause the suppression of alpha waves (Valentino et al., 1993).

1.2.2. Theta spectral power variations

On the other hand, theta spectral power is thought to increase along with numerous other factors, such as time pressure (Slobounov et al., 2000) cognitive resource demand (see Vidulich and Tsang, 2012 for a review) and the number of concurrent tasks to be processed (Yamada, 1998; Fairclough and Venables, 2006; Fairclough et al., 2005). This increase is mainly observed in fronto-central regions, though these locations may be modulated by age (McEvoy et al., 2001). However, using increasingly difficult tasks to elicit consistent patterns of increasing theta spectral power has been proved inefficient in numerous studies (Käthner et al., 2014; Fournier et al., 1999; Baldwin and Penaranda, 2012; Funke et al., 2013) or revealed inconsistent patterns (Brookings et al., 1996; Pigeau et al., 1988). For example, Gevins et al. (1995) reviewed three of the experiments of their team using tasks of increasing difficulty (Gevins and Schaffer, 1980; Gevins et al., 1979a, 1979b). None of these revealed a significant increase of theta band power in relation to the difficulty of the task. Increasing the number of concurrent tasks to be performed simultaneously, also led to either no pattern or an inconsistent one in different studies (Holm et al., 2009; Fournier et al., 1999). Moreover, according to a review by Kramer (1990), theta band power should decrease with an increasing cognitive workload, a result already reported in Sirevaag et al. (1988) and in Natani and Gomer (1981).

1.2.3. Hypothesis on results differences

The lack of consistent variations in EEG theta rhythms and an incoherent pattern might arise from two possible methodological issues. Either these studies used paradigms where the low workload condition demanded too many cognitive resources to allow for significant variations with other workload conditions (see Kramer, 1990 for a discussion of this point) or the inter-individual differences overshadowed the variations elicited by the task manipulations. The first explanation was suggested by Kramer (1990) who compared EEG patterns with regard to theta rhythm in three studies (Sirevaag et al., 1988; Natani and Gomer, 1981; Pigeau et al., 1988). He remarked that the differences in theta rhythm were due to differences in the difficulty in the initial task.

The second concerns a statistical issue occurring when too few