

## Psychophysiological investigation of vigilance decrement: Boredom or cognitive fatigue?

Nathalie Pattyn<sup>a,b,\*</sup>, Xavier Neyt<sup>c,1</sup>, David Henderickx<sup>a,2</sup>, Eric Soetens<sup>a,2</sup>

<sup>a</sup> Department of Cognitive & Biological Psychology, Vrije Universiteit Brussel, Pleinlaan, 2, 1050 Brussel, Belgium

<sup>b</sup> Department of Behavioral Sciences, Royal Military Academy, Renaissancelaan, 30, 1000 Brussel, Belgium

<sup>c</sup> Signal & Image Centre, Royal Military Academy, Renaissancelaan, 30, 1000 Brussel, Belgium

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### Abstract

The vigilance decrement has been described as a slowing in reaction times or an increase in error rates as an effect of time-on-task during tedious monitoring tasks. This decrement has been alternatively ascribed to either withdrawal of the supervisory attentional system, due to underarousal caused by the insufficient workload, or to a decreased attentional capacity and thus the impossibility to sustain mental effort. Furthermore, it has previously been reported that controlled processing is the locus of the vigilance decrement. This study aimed at answering three questions, to better define sustained attention. First, is endogenous attention more vulnerable to time-on-task than exogenous attention? Second, do measures of autonomic arousal provide evidence to support the underload vs overload hypothesis? And third, do these measures show a different effect for endogenous and exogenous attention? We applied a cued (valid vs invalid) conjunction search task, and ECG and respiration recordings were used to compute sympathetic (normalized low frequency power) and parasympathetic tone (respiratory sinus arrhythmia, RSA). Behavioural results showed a dual effect of time-on-task: the usually described vigilance decrement, expressed as increased reaction times (RTs) after 30 min for both conditions; and a higher cost in RTs after invalid cues for the endogenous condition only, appearing after 60 min. Physiological results clearly support the underload hypothesis to subtend the vigilance decrement, since heart period and RSA increased over time-on-task. There was no physiological difference between the endogenous and exogenous conditions. Subjective experience of participants was more compatible with boredom than with high mental effort.

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### 1. Introduction

This study reports a psychophysiological investigation of vigilance through behavioural, physiological and self-report measures. The aim was to gain a better understanding of the mechanisms at stake in sustaining attention by targeting two different

modes of attentional control: endogenous and exogenous attention. The addition of cardio-respiratory recordings to infer autonomic activation was aimed at differentiating between the “overload” hypothesis and the “underload” hypothesis as subtending the vigilance decrement.

A crucial determinant of cognitive performance is the ability to maintain the focus of cognitive activity on a given stimulation source or task, in other words, sustained attention or vigilance. Traditionally, sustained attention tasks have been long detection tasks of scarcely occurring signals, where a decrement appears after 20 to 30 min, expressed as an increase in reaction times (RTs) or an increase in lapses or error rates [1–4]. The data on sustained attention can be interpreted in terms of automatic and controlled processing [5]. This view is based on the model describing human performance as the result of two qualitatively different forms of

\* Corresponding author. Department of Cognitive & Biological Psychology, Vrije Universiteit Brussel, Pleinlaan, 2, 1050 Brussel, Belgium. Tel.: +32 2 629 15 94, +32 476 66 12 03 (Mob); fax: +32 2 629 24 89.

E-mail addresses: npattyn@vub.ac.be (N. Pattyn), xavier.neyt@rma.ac.be (X. Neyt), david.henderickx@vub.ac.be (D. Henderickx), esoetens@vub.ac.be (E. Soetens).

<sup>1</sup> Tel.: +32 2 742 64 73; fax: +32 2 742 64 72.

<sup>2</sup> Tel.: +32 2 629 28 73; fax: +32 2 629 24 89.

information-processing, namely automatic and controlled processing [6]. Controlled processing is described as serial in nature, requiring effort, under an individual's direct control, and not dependent on extensive practice to reach asymptotic performance. Automatic processing is considered as parallel in nature, not limited by short-term memory capacity, requiring little or no effort, not under the subject's direct control and requiring extensive consistent training to develop (at least for higher-level cognitive functions) [6]. Controlled processing has been shown to be the locus of the vigilance decrement [5]. This has been confirmed by research showing that increasing exogenous support to alternative response selection in a sustained attention to response task improved performance by reducing the need for endogenous attentional modulation of behaviour [7]. However, large vigilance decrements have been described for tasks where there is obviously a strong automatic component, like the psychomotor vigilance task (PVT). These findings have been explained by pointing out that a distinction between automatic and controlled processing based on task characteristics is an oversimplification, since every cognitive process requires the interplay between both modes [8]. Thus, although descriptions of the vigilance decrement in terms of automatic and controlled processes intuitively seem to provide an etiological description of this decrement, they still remain rather vague. No effort is made to understand how both mechanisms interplay, and which of the underlying processes are assumed to deteriorate over time. This automatic vs controlled difference has been described for vigilance performance [9] as the distinction between, on the one hand, the ability to self-sustain mindful processing of stimuli over time-on-task (self-sustained attention) and, on the other hand, exogenously controlled alertness governed by stimulus characteristics such as novelty or salience. This distinction thus draws further on the one made between automatic and controlled processing, and can be further defined as exogenous and endogenous attention. Exogenous attention refers to the automatic attraction of attention driven by external physical events, such as the sudden appearance or physical change of a stimulus. This mode of attentional orientation is considered to function in a bottom-up manner and not under the subjects' voluntary control. Endogenous attention, on the other hand, refers to actively and deliberately directing attention to what we believe is important, for example after being instructed to focus attention on a defined target. This is a typical top-down controlled mechanism, requiring the subjects' attentional effort. The difference between both types of attentional mechanisms was evidenced by means of a cueing paradigm [10]. Subjects had to detect a target, presented to the left or to the right of a fixation point. The target display was preceded by a cue, indicating the likely location of the target (e.g. 80%). Exogenous cueing involved presenting a brief flash to the left or to the right of fixation. Endogenous cueing was accomplished by presenting a central arrow pointing to the left or to the right. This design elicited a typical cost-benefit pattern according to the validity of the cues, that is, RTs were faster when the target appeared in the cued location (thus, after a valid cue), as compared to a neutral condition without cue, and RTs were slower when the wrong location was indicated (thus, after an invalid cue). Previous research has shown endogenous attention to be a controlled

processing mode, since it is dependent on the observer's goals and expectancies, whereas exogenous attention, with its bottom-up functioning, can be viewed as a far more automatic process [10].

This difference between endogenous and exogenous attention in vigilance has been investigated in a more applied setting [11], where vigilance displays for target acquisition with unmanned aerial vehicles (UAV) were studied. Two types of display were investigated: sensory displays, where changes in physical attributes of stimuli were the critical signals for detection, thus tapping exogenous attention, and cognitive displays, where symbolic manipulations were required to define critical signals, thus relying on endogenous attention. These results showed that a sensory display format resulted in more efficient detection and a smaller performance decrement over time (30 min), whereas cognitive displays led to worse performance, and a larger decrement over time. This distinction thus suggests a link between vigilance research showing controlled processes to be most vulnerable to performance decrements over time, and the endogenous attention component, seeming to be also the most sensitive to vigilance decrements.

In most research on vigilance to date, mainly endogenous attention was tested. This appears clearly in the first experimental report on vigilance [1], where the stimuli were described as follows: "difficult to perceive because the subject had no more than a glimpse of each of these barely visible stimuli". Since previous research seems to point to controlled processes as the locus of the vigilance decrement, one can expect endogenous attentional control to be the most vulnerable to deterioration. Using an experimental paradigm differentiating more automatic attraction of attention (i.e. exogenous) vs more controlled allocation of attention (i.e. endogenous) might therefore offer additional insights to the description of the vigilance decrement.

We applied a similar conjunction search to the study of vigilance as recently reported [12], but with a cueing paradigm derived from the Posner task [10]. This would allow us to study the evolution with time-on-task of the use of the informative value of the cue. Indeed, an endogenous cue requires more controlled processing to be effectively used, whereas an exogenous cue relies on more automatic processes. Different time-effect on both type of cues, and the consequences on the conjunction search performance could further define the different attentional mechanisms at stake in vigilance.

Several hypotheses have been described to account for the vigilance decrement. Some investigators, e.g. [7,9,13], state that the vigilance decrement is a consequence of attentional withdrawal of the supervisory attentional system, due to underarousal caused by the insufficient workload inherent to typical vigilance tasks. Evidence supporting this hypothesis can be found in the fact that a correlation was observed between task-irrelevant mental activities and attentional lapses during a vigilance task [14], as well as in findings showing the highest performance decrements in sustained attention to be associated with lower cortical tonic activation and lower phasic ERP responses [15]. However, other authors, e.g. [4,16,17], view the decrement as the result of a decrease of attentional capacity over time-on-task and thus as the impossibility to sustain the effort, due to the too high mental workload, as measured by, for example, the NASA Task Load Index (NASA-

TLX) [4]. This could be summarized as the boredom vs cognitive fatigue hypothesis. With regard to where both hypotheses are positioned on the spectrum of workload evaluation, this distinction could be summarized as the “underload” vs “overload” view. Whereas one could argue that the term “overload” is incorrectly used in this context, since the detection task does not involve extremely high demands per se, in contrary to other tasks, such as the digit-span working memory task where the difficulty level can be varied according to the choice of stimuli, we still feel the description of the “performance failure in vigilance as a consequence of a depletion in information-processing resources reflecting limitations in effortful attention” [4,17] observed in conjunction with high ratings on several workload indices can be summarized as “overload”. The apparent paradox between the “underload” hypothesis, where vigilance decrements are shown to be associated with mind-wandering, according to the subjective experience of participants, and the “overload” hypothesis, where the vigilance decrements is shown to be associated to high evaluations of workload on the NASA-TLX, for similar types of tasks, certainly calls for further investigation.

While there have been sufficient attempts to quantify workload through physiological indices, few research has investigated the “underload” side of the workload spectrum. However, boredom and complacency may have dramatic consequences on work performance, just as an “overload” leading to saturation of the human operator [18]. This concept of an optimal level of workload for performance, with both ends of the spectrum, either too high or too low, leading to decrements could be compared to the Yerkes–Dodson law [19], where an optimal level of arousal is described for optimal performance, with both underarousal and overarousal being detrimental.

Recent results suggest the existence of such an optimum of workload. Indeed, matching task difficulty to the arousal of the subject was showed to enhance vigilance performance [12]. Task difficulty was varied through different array sizes in a simultaneous discrimination task in function of the Engagement Index, EI, computed as the ratio of EEG bandwidth power beta / (alpha + theta). The use of this EI was based on the notion that increases in arousal and attention are reflected in the beta bandwidth, while decreases are reflected in the alpha and theta bandwidth [20]. This experiment included feedback conditions to match task difficulty to operator engagement, i.e. increasing difficulty when engagement was low and decreasing difficulty when engagement was high. The results [12] showed this matching to be effective in alleviating the effects of time-on-task, and it was also reported that participants showed a low EI during the majority of the task in the uncoupled feedback condition. These findings confirmed previous reports [21] and were further validated by more recent research, showing the quality of vigilance performance to be related to a higher cortical arousal [15], and thus seem to be in favour of the “underload” hypothesis, with vigilance tasks rather decreasing arousal, which is more compatible with an “underload” view than with an “overload” in terms of workload. Furthermore, the fact that the increase in task difficulty, applied when the EI decreased, alleviated the vigilance decrement is simply contradictory with a depletion of attentional resources subtending this decrement.

These conclusions were based on cortical arousal. The question thus remains whether systemic autonomic arousal would undergo a similar evolution as the previously described cortical arousal. To investigate this, we measured cardio-respiratory activity of participants, and used the electrocardiogram (ECG) and the respiratory volumes and frequency to compute the activation of both the sympathetic and the parasympathetic branch of the autonomic nervous system (ANS). To summarize, the ANS is subdivided in two anatomically and functionally distinct systems: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). Whereas the sympathetic branch can be viewed as the “activating” side of the ANS, responsible for example for the fight-or-flight response when confronted with danger, the parasympathetic branch can be viewed as the “relaxing” side, lowering spontaneous heart rate for example. The power spectrum density calculation of heart period time series has been shown to provide insight into the respective activation of the sympathetic and parasympathetic branches [22]. Furthermore, recordings of heart activity and the derived computation of respective PNS and SNS activation have been repeatedly applied to measure workload variations with given tasks [e.g. [23]].

The present experiment aimed at answering three questions. First, whether endogenous and exogenous attention would show a different resistance to vigilance decrement over time. Based on the literature on the evolution of controlled processes over time, we expect endogenous attention to be more vulnerable to time-on-task, and thus, the use of the endogenous cue to be less efficient with time. Second, should endogenous and exogenous attention evolve differently over time, whether this difference in cognitive processes would be reflected in autonomic responses. Third, whether a sustained attention task would result in a decreased activation as measured by systemic autonomic responses – increased PNS activity and decreased SNS activity – confirming previous EEG data and in favour of the “underload” hypothesis [12,15,21].

## 2. Methods

### 2.1. Subjects

Participants ( $N=21$ ) were students in their first year Social and Military Sciences at the Royal Military Academy of Brussels. All participants had normal or corrected-to-normal vision and participated voluntarily. This experiment had been approved by the Bio-Ethical Review Board of Defence. All subjects signed an informed consent form prior to participation. Prior to the experiment, subjects participated in a short Posner task [10]. This procedure aimed at categorising the subjects in two matched groups in terms of attentional performance and reaction time. Subjects were assigned to either the “Endogenous” group or the “Exogenous” group based on their results for the preliminary basic attention test, to ensure a matching of both groups on a basic attentional performance.

### 2.2. Apparatus

All experimental sessions were planned similarly: same location, same time of day, with sessions starting between 16.00

and 18.00. During the testing, subjects wore a headset to be isolated from possibly disturbing environmental noise. Experiments were generated with the E-prime 1.1 software [24]. Stimuli were presented on a Sony Multiscan G 400 (19 inch) monitor, at 50 cm viewing distance. Responses were registered through the keyboard of an IBM A 21p PC. Reaction times (RTs) and error rates (ERs) were recorded. ECG and respiration were obtained non-invasively through the LifeShirt system (VivoMetrics, Inc).

### 2.3. Procedure

Before the start of the cognitive testing, participants were equipped with the LifeShirt. To yield baseline values for their physiological parameters, these were recorded during a 10 min rest period. Afterwards, the cognitive task started. Each session began with on-screen instructions. After a 60-trials practice block, subjects were given a 1 min rest before the start of the experimental blocks.

Subjects subsequently saw three types of displays: fixation, cue, and target display on each trial. The fixation consisted of a cross in the middle of the screen, between 6 square boxes: 3 right and 3 left from the cross. The six boxes and the cross were in the center of the screen, in a  $11 \times 97.5$  mm area, measuring  $11^\circ 8'$  horizontal and  $1^\circ 17'$  vertical visual angle from a viewing distance of 50 cm. The boxes were grey against a white background. Stimuli appeared inside these boxes.

For the exogenous condition, either the three right boxes or the three left boxes increased in brightness to indicate where the target would likely appear (valid or invalid cue). Fig. 1 illustrates the sequence of fixation display, cue display and target display for an exogenous cue. For the endogenous condition, the cue display consisted of an arrow, replacing the central cross, indicating the likely location of the target to come. In both endogenous and exogenous conditions, the cue could be valid or invalid and appeared for 800 ms.

The target display consisted of the fixation display with the addition of coloured geometrical shapes within the boxes. Two different shapes were used, a star and a circle, and two different colours, red or green. Participants were instructed to detect the target stimulus, which was a green star. The target display remained on-screen until the response was given by the subject.

The target had a maximum presentation duration of 3000 ms. To indicate the presence or absence of the target, participants were

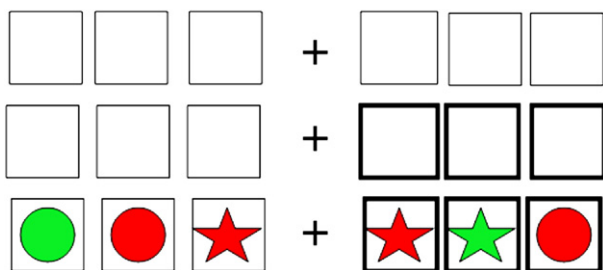


Fig. 1. Course of a valid trial in the exogenous condition. Upper row: fixation display; middle row: exogenous valid cue display (800 ms): the boxes are brightened in the location where the target will appear in the following display; bottom row: target display, with the green star being the target. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

required to press the keys “1” or “3” of the numeric pad. The mapping of the response keys was counterbalanced across subjects. There was an equal probability for the target to appear right or left.

The response-stimulus interval (RSI) was variable, and could be 7 s, 15 s, 23 s, 31 s or 39 s (mean: 23 s). The total duration of this vigilance task was 1.5 h. Presentation of the different trials and different RSIs was randomized within three 30 min blocks. In each block, 70 trials were presented, with 40 target-present trials. From these 40 target-present trials, there were 30 following a valid cue and 10 following an invalid cue.

After completion of the task, subjects were asked, first, whether they had experienced any disturbing factor while performing the experiment, and second, how they had coped with the long time-on-task and whether they had used a strategy allowing them to keep concentrated. Participants were also asked to rate the quality of their performance for the three time blocks on visual analogue scales.

### 2.4. Recording of physiological signals

Cardio-respiratory recordings were obtained non-invasively through the LifeShirt system (VivoMetrics, Inc). The electrocardiogram (ECG) was measured through three patch electrodes, generating a standard single lead ECG (D II), recorded at 200 Hz. Respiratory movements were measured by respiratory inductive plethysmography: abdominal and ribcage excursions were recorded at 50 Hz.

All data were visually inspected for artefacts and correct detections. In case of ectopic beats or erroneous detections, the data were manually corrected (removal of erroneous detection/artefact followed by a cubic spline interpolation).

Analysis of the recorded signals was done by proprietary algorithms in the dedicated VivoLogic software (VivoMetrics, Inc). The ECG signal was digitally up-sampled to 1000 Hz, and the R-wave detection was achieved through a derivative-based algorithm. The timing of the detected R-wave was used to generate the RR-interval (RRI). The spectral analysis of the tachogram of intervals was implemented through a Fast Fourier Transform, using a Welch periodogram, i.e. a Hanning window with 65 % overlap. This generated power of the low frequency component, comprised between 0.04 Hz and 0.15 Hz [22]. This power spectrum was then used to compute normalized LF power (i.e. the ratio between LF power and total power), as an index of sympathetic activation. RSA was computed through the peak-valley method [25] to reflect parasympathetic tone. Respiratory frequency ( $F_{resp}$ ) and tidal volume (TV) were computed in VivoLogic. For calculation of volume, we used a qualitative calibration procedure (Qualitative Diagnostic Calibration, as implemented in VivoLogic 2.9) for each individual data-file, since the relevant information was the variation in tidal volume across the experimental protocol, and not its absolute value per se.

## 3. Results

### 3.1. Behavioural results

Overall, RTs were faster in the exogenous condition. Both endogenous and exogenous conditions show an increase from



the first to the second time block, which is more pronounced after invalid cues (see Fig. 2). From the second to the third time block, there is a large increase of the validity effect (the difference between RTs after invalid cues and RTs after valid cues) in the endogenous condition, mainly due to the high RT after invalid cues, while RTs after valid cues decrease. Considering the very high variance of these results, we analysed them after applying a jackknife procedure [26], which has been shown to be applicable in factorial design, provided a correction factor is applied to the  $F$ -value obtained [27]. The results reported here, as well as the outcome of the statistical analysis, are based on the jackknifed values and the implemented corrections.

These data were submitted to a  $3 \times 2 \times 2$  ANOVA, with time-on-task and validity as within-subject factors, and condition as between-subject factor. This yielded a significant main effect of time,  $F(2,40)=12.9$ ,  $p<0.01$ , of validity  $F(1,20)=218.9$ ,  $p<0.01$  and of condition  $F(1,20)=4.7$ ,  $p<0.01$ , as well as significant interactions between validity and condition  $F(1,20)=5.1$ ,  $p<0.01$ , between time and validity  $F(2,40)=3.36$ ,  $p<0.05$  and between time, validity and condition  $F(2,40)=3.36$ ,  $p<0.05$ . To further unravel these interactions, separate ANOVAs for the endogenous and the exogenous condition were performed.

The  $3 \times 2$  ANOVA for the endogenous condition showed a significant effect of time  $F(2,9)=5.57$ ,  $p<0.01$  and of validity  $F(1,10)=54.8$ ,  $p<0.001$ , as well as a significant interaction between both  $F(2,9)=3.34$ ,  $p<0.05$ . Subsequent contrast analysis for time revealed that the difference between the first and the second time block  $F(1,10)=6.5$ ,  $p<0.01$ , as well as between the first and the third time block  $F(1,10)=8.9$ ,  $p<0.01$  were significant, but not between the second and the third time block ( $F<1$ ). Contrast analysis for the time  $\times$  validity interaction revealed a different pattern: the only significant difference was evidenced between the first and the third time block [ $F(1,10)=5.95$ ;  $p<0.05$ ]. These results show two different effects of time on RTs after endogenous cues: first, an overall slowing of RTs, which appears after the first time block and does not increase

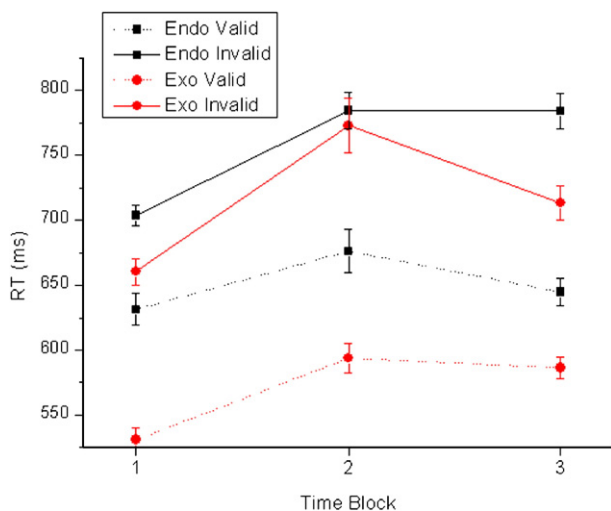


Fig. 2. The evolution of reaction times (ms) over time blocks (30 min each) after valid (dotted lines) and invalid (full lines) cues, for the endogenous (squares) and exogenous (circles) conditions.

Table 1

Mean RTs (ms) and jackknifed standard deviations on target-absent trials for endogenous and exogenous cueing over the three 30 min time blocks

Time block	1	2	3
Endo	748.7 (10.2)	778.8 (16.3)	789.3 (14.8)
Exo	631.2 (6.5)	684.2 (14.1)	655.2 (10.2)

subsequently; second, a change in the use of the cue, which appears mainly in the third time block.

For the exogenous condition, the  $3 \times 2$  ANOVA showed a significant effect of time  $F(2,8)=7.51$ ,  $p<0.01$  and of validity  $F(1,9)=240.6$ ,  $p<0.001$ , but no interaction between both  $F(2,8)=1.6$ ,  $p>0.1$ . Contrast analysis for time revealed a similar pattern to the one described for the endogenous condition, namely significant differences between first and second time block  $F(1,9)=10.37$ ,  $p<0.01$ , as well as between the first and the third time block  $F(1,9)=8.9$ ,  $p<0.01$ , but not between the second and the third time block  $F(1,9)=2.27$ ,  $p>0.1$ . For the exogenous condition, the effect of time can thus be described as the sole slowing of responses after the first time block, with no modification of the validity effect.

These data describe RTs on target-present trials. However, RTs for correct responses on target-absent trials, which are presented in Table 1, also showed an effect of time. These results show again faster responses after exogenous cueing, and an effect of time most apparent in the difference between the first and the second time block.

These data were analysed with a  $3$  (time)  $\times$   $2$  (condition) ANOVA, showing a significant effect of time  $F(2,40)=4.01$ ,  $p<0.05$  and a significant effect of condition  $F(1,20)=14.7$ ,  $p<0.01$ , but no interaction between time and condition ( $F<1$ ). Contrast analysis for time confirmed that the slowing of responses appeared after the first time block, but did not increase further, since the difference between first and second time block  $F(1,20)=7.49$ ,  $p<0.01$  as well as between first and third time block  $F(1,20)=4.25$ ,  $p<0.05$  were significant, while the difference between the second and the third time block was not ( $F>1$ ).

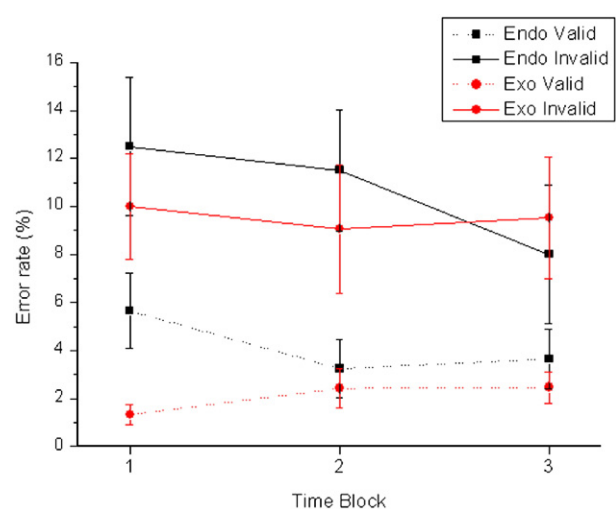


Fig. 3. The evolution of error rates (%) over time-on-task after valid (dotted lines) and invalid (full lines) cues, for the endogenous (squares) and exogenous (circles) conditions.

Error rates are presented in Fig. 3. The overall error rates are smaller in the exogenous conditions, with a slight decrease of the validity effect over time, while there is a tendency for a decrease in errors over time in the endogenous condition.

After an arcsine transformation, these data were submitted to a  $3 \times 2 \times 2$  ANOVA, which only yielded a significant main effect of validity  $F(1,20)=20.48$ ,  $p<0.001$ , but no effect of time ( $F<1$ ) nor condition  $F(1,20)=2.5$ ,  $p>0.1$ . None of the interactions revealed significance either.

In addition to these error rates for the target-present trials, error rates for the target-absent trials were also examined. These showed a different evolution for both conditions. For endogenous cueing, percentage of errors first decreases from 7% to 4% and increases in the last time block to 8%, while for exogenous cueing there is a steady decrease of errors: from 6% over 3% to 2% in the last block. After an arcsine transformation, these data were analysed with a  $3 \times 2$  ANOVA, showing a significant effect of time  $F(2,40)=5.74$ ,  $p=0.005$  as well as a significant interaction between time and condition  $F(2,40)=5.04$ ;  $p=0.009$ , but no main effect of condition  $F(1,20)=2.5$ ,  $p>0.1$ .

### 3.2. Physiological results

Fig. 4 shows the evolution of RR-interval (RRI), respiratory frequency ( $F_{\text{resp}}$ ) and tidal volume (TV) for baseline recordings (10 min) and the three time blocks (30 min each) of the vigilance experiment. Fig. 5 depicts the concurrent evolution of respiratory sinus arrhythmia (RSA), being an indicator of parasympathetic tone and of the normalized low frequency component (LFnorm) of the power spectrum of heart period, being an indicator of sympathetic activation. As shown on these figures, the reactivity between baseline and task is expressed as an increase in breathing frequency ( $F_{\text{resp}}$ ), a decrease in RSA, a slight increase in tidal volume (TV) and, surprisingly, an increase in RRI for both groups. They only differ in their reactivity with regard to LFnorm: whereas it increases from baseline to task for the endogenous group (as expected), it decreases for the exogenous group.

These data were submitted to a repeated measures multivariate analysis of variance (MANOVA), with group as a between-subject factor (2 levels) and time (4 levels) as a within-subject factor. This showed no significant effect of group  $F(1,20)=1.64$ ,

$p>0.1$ , a main effect of time  $F(3,60)=3.54$ ;  $p=0.007$  and no interaction between group and time ( $F<1$ ). It thus seems that there were no differences between subjects performing the endogenous and the exogenous cueing tasks, despite the observed differences in cognitive results.

The univariate ANOVAs following up the significant MANOVA for time showed the only significant variation was for  $F_{\text{resp}}$   $F(3,60)=4.2$ ,  $p=0.009$ . Subsequent contrast analysis for this variation of breathing frequency showed that the only significant differences were between baseline recordings on the one hand and the three experimental blocks on the other hand. These results thus suggest that the significant effect of time was due to the reactivity between baseline and task for breathing frequency. There is no evidence of any reactivity effect in heart period (RRI), on the contrary, it shows an inverse evolution to the usual reactivity effect, and no evidence either of any significant effect of time-on-task. However, as suggested by Figs. 4 and 5, this effect of time-on-task is small yet present as an overall decrease in autonomic activation (increased RRI, increased RSA, decreased LFnorm, with stable respiratory parameters). To further investigate this effect of time-on-task, subsequent analyses were performed on the three experimental blocks, leaving out the baseline values, which allowed us to investigate the effect of time-on-task, while leaving the variation due to initial reactivity out.

Considering the large interindividual variation present for RRI, RSA and LFnorm, as depicted in Figs. 4 and 5, it is not surprising the small effect of time-on-task fails to reach significance. This interindividual variability is a common issue in psychophysiology, and several within-subject standardization methods have been described, as previously reported [28]. We applied the range-correction procedure [29] to rescale the data for each subject. This transformation allows standardizing for individual differences in baseline and ranges, by expressing each individual's score ( $A$ ) in function of his/her own minimum value ( $X$ ) and his/her own range, being the difference between maximal and minimal value ( $Y-X$ ). Each score  $A$  is replaced by the value  $(A-X)/(Y-X)$ . Values for each subject are thus expressed on a range between 1 and 0. This allowed us to investigate whether the physiological parameters showed an evolution over time-on-task, independently from baseline-task reactivity. These rescaled data are presented in Table 2.

These data were again submitted to a repeated measures MANOVA with group as a between-subject factor and time as a

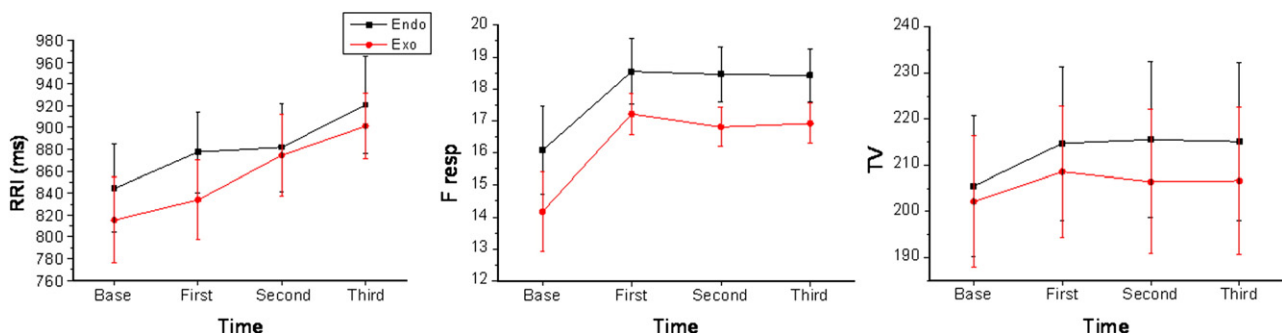


Fig. 4. RRI (ms), breathing frequency ( $F_{\text{resp}}$ ;  $\text{min}^{-1}$ ) and tidal volume (ml) for the endogenous (Endo) and exogenous (Exo) groups for baseline recordings and the three 30 min time blocks of the experiment.

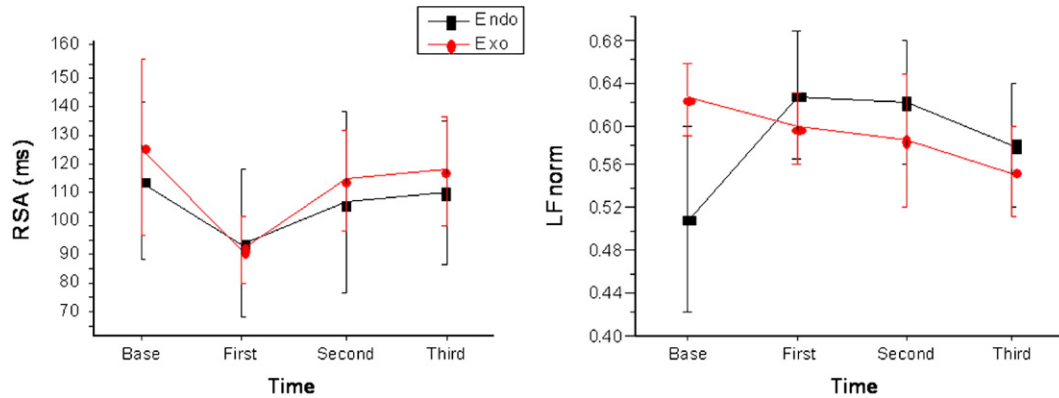


Fig. 5. RSA (ms) and LFnorm endogenous (Endo) and exogenous (Exo) groups for baseline recordings and the three 30 min time blocks of the experiment.

within-subject factor. Again, this yielded no effect of group  $F(1,20)=2.16, p>0.1$ , but a significant main effect of time  $F(2,40)=23.13, p<0.001$  and no interaction between group and time ( $F<1$ ). The univariate ANOVAs for time showed a significant effect for RRI  $F(2,40)=25.87, p<0.001$  and for RSA  $F(2,40)=8.67; p=0.001$ , but not for LFnorm  $F(2,40)=2.4, p>0.1$ . Further contrast analysis of the significant effect of time for RRI and RSA revealed that all time blocks differed significantly from each other for RRI [1 vs 2 ( $p=0.03$ ); 1 vs 3 ( $p<0.001$ ); 2 vs 3 ( $p<0.001$ )], but that the differences for RSA were only significant when comparing to the first time block [1 vs 2 ( $p=0.015$ ); 1 vs 3 ( $p<0.001$ ); 2 vs 3 ( $p>0.1$ )].

These results thus show a decrease of heart rate over time, no effect on respiratory parameters, an increase in parasympathetic tone as indexed by RSA and no significant effect on sympathetic tone, as indexed by LFnorm. There was no difference between experimental groups in this evolution over time-on-task.

### 3.3. Subjective results

All the participants mentioned the long duration of the experiment and the long RSIs as disturbing factor. No other environmental or task-related variable was cited. 16 out of 21 subjects reported task-irrelevant mental activity to cope with the monotony of the task (mental singing, counting, irrelevant thoughts etc.) or some rhythmic leg or finger movements. 17 out of 21 subjects reported they felt their performance was worse during the second half hour of the task. The ratings on the visual analogue scales for the three time blocks showed a mean score of 71.7 for the first time block, 47.9 for the second time block

and 78.9 for the third time block. There were no differences in subjective reports between groups.

## 4. Discussion

In this experiment, three questions were investigated. First, whether endogenous and exogenous attention would show different vulnerability to time-on-task. The second question targeted the possible reflection of these different cognitive mechanisms in cardio-respiratory measurements and autonomic activation. The third question aimed at settling the existing controversy between the “overload” and the “underload” hypotheses as mechanisms subtending the decrease in vigilance over time, by investigating the systemic autonomic activation during a vigilance task.

Endogenous and exogenous attention showed a different evolution over time. Indeed, the RT data from Fig. 2 show a dual effect from time-on-task. Firstly, an overall slowing of responses between the first and second time block, which is present for both endogenous and exogenous conditions, being more pronounced in the endogenous condition. Secondly, a larger validity effect over time in the endogenous condition, mainly due to slower RTs after invalid cues, which is present in the second and third time block. This might be accounted for by a slower change of location focus after an endogenous invalid cue in the last time block, thus expressing a higher switching cost (changing the focus from one side of the fixation cross to the array on the other side) as an effect of time-on-task.

Overall, the cognitive results indicated a dual effect of time. First, there was an overall slowing of responses after the first time block. According to the literature describing the performance decrement in the usual vigilance tasks, it appears after approximately 20 to 30 min [1]. Second, an additional cost appeared, expressed as a higher switching cost after an invalid cue in the endogenous condition, which was most apparent in the third time block. Furthermore, these results confirm the more efficient performance after exogenous cueing: faster RTs and smaller error rates, as well as less vulnerability to time-on-task. The effect of time-on-task is not indexed as an increase in attentional lapses, since errors do not increase across time blocks. This is a notion to emphasize. Indeed, as previously reported, [30], the traditional study of vigilance, especially in studies of sleep loss, has stressed the “lapse hypothesis”: the

Table 2  
Range-corrected RRI, RSA and LFnorm data for the endogenous (Endo) and exogenous (Exo) groups during the three subsequent experimental blocks

Group	Time block	RRI	RSA	LFnorm
Endo	1	0.06	0.45	0.78
	2	0.36	0.45	0.70
	3	0.61	0.91	0.48
Exo	1	0.24	0.26	0.55
	2	0.56	0.64	0.55
	3	0.77	0.98	0.28

momentary performance lapses, i.e. failures to detect critical signals, defining the vigilance decrement. However, this definition seems too narrow, since it does not account for slowing of reaction time, nor for specific shifts in processing strategies or faulty decision making [30]. Our results thus showed a dual effect of time-on-task on reaction times, and no effect on overall error rates. One limitation of this research is that we did not document the physiological changes occurring right before, during, and after such attentional lapses, which could provide valuable information on the nature of these brief decrements.

The subjective reports of participants on the overall quality of their performance reflected the overall effect of time-on-task on RTs: the worst performance was seen in the second time block. For this detrimental effect of time, subjects were thus able to correctly evaluate their performance.

Despite the different effects of time-on-task for behavioural results, there were no differences between the autonomic responses, as expressed in cardio-respiratory parameters, elicited by endogenous and exogenous conditions. This difference in cognitive processes might be too fine-grained to be reflected in systemic activation.

Two different sources of variation were evidenced in the cardio-respiratory data. The first one is the activation response, which is the result of the comparison between baseline recordings and task recordings. This difference between baseline and task was only significant for breathing frequency. Heart period did not show any significant decrease, unlike numerous previous findings in the literature. However, this task may be considered as generating a low workload: the main challenge of long vigilance experiment is sustaining attention over time, not performing the task itself. Since heart rate has been repeatedly described as an indicator of task difficulty and workload, as reflected by the activation response [31], it might be that the attention task was not demanding enough to elicit cardiac reactivity. We suggest it was not the paradigm per se that lacked “workload”, but probably the low event rate. Indeed, when compared to previous studies with 10 events per minute [21], 15 and 40 events per minute [11] or 30 events per minute [32], the chosen mean event rate of approximately 2 to 3 per minute may seem very low. The reason for this methodological choice was the investigation of a broad range of response-stimulus intervals, although that aspect of the results is not discussed here.

Event rate has been previously described as an important factor influencing performance in vigilance. The hit rate has been reported to show a threefold decrease when event rate is increased from 5 events to 30 events per minute [33]. However, the previously described research on sensory vs cognitive displays for vigilance performance [11] included a comparison of two event rates, 15 and 40 per minute, and this factor did not seem to affect neither the quality of the detection performance nor the workload evaluation according to the NASA-TLX index. Thus, although the event rate applied in the present research is indeed at the low end of the spectrum, it does not weaken the observed effects.

The fact that autonomic recordings showed a reactivity for breathing frequency but not for cardiac parameters indicates respiration might be more sensitive to workload than heart period.

The second source of variation was the effect of time-on-task. Though the effect was small, requiring a rescaling of the data to show significance, physiological results are clearly in favour of the “underload” hypothesis. Indeed, the lack of cardiac reactivity from baseline to task, as well as the further decrease of heart rate over time-on-task can hardly be consistent with an overload of the subject’s attentional capacity and thus, with “the impossibility to sustain the effort due to the mental workload” [4,12]. Furthermore, the lack of variation of sympathetic activation and the increase of parasympathetic activation point towards disengagement of the subjects from the task, rather than overactivation. According to the taxonomy describing autonomic activation [34], these results thus suggest uncoupled activation: an increased parasympathetic activity with no concomitant increase or decrease in sympathetic activity. Furthermore, the lack of variation of respiratory indices during the vigilance task, as shown by the stable results for breathing frequency and tidal volume, allows us to interpret the increasing RSA as a marker of “pure” increase in parasympathetic tone. These results thus confirm previous EEG data [12,15,21], by showing systemic measures of autonomic activation to index what was termed “task disengagement”. Furthermore, the fact that a majority of subjects reported task-irrelevant mental activity is not compatible with an overloaded attentional capacity. This also confirms previous findings [14] that under conditions of low target probability, attention tends to drift away from task relevant material. Furthermore, smaller vigilance decrements were evidenced in subjects reporting task-irrelevant thoughts, i.e. keeping themselves busy [14]. These reports all indicate vigilance tasks to induce attentional withdrawal, rather than overload of attentional capacity. After the present experiment, the majority of subjects reported task-irrelevant thoughts or mental activities (e.g. singing), thus subjectively showing attentional disengagement. This seems hardly compatible with the “overload” account. However, alternatively, it could be viewed as a depletion of optimal resources because of underarousal, this resource depletion further leading to a decline in task goal activation or an increased propensity to distraction and disengagement. This situation might reflect a different signal-to-noise ratio within the system, whereby the signal strength would reflect the resources deployed to the task goal and the noise would reflect background levels of arousal related to task-irrelevant factors. This would be an argument in favour of considering both hypotheses, underload and overload, not as opposite views but really as two sides of the same coin. However, this would still imply that there are sufficient resources at hand, only that the subject does not allocate these to the vigilance task. Therefore, if considering the workload aspect of the task, one could hardly consider vigilance task to be overloading subjects’ attentional capacity.

Considering the underload view and the feedback on subjective experience of participants showing task-irrelevant thoughts, it might be that vigilance tasks are merely measuring boredom. The subjective experience of boredom has been described as composed of a cognitive and affective component [35]. The cognitive component arises from the operator’s perception of the demands, which are imposed by the task. If the task is perceived as meaningless and lacking challenge, requiring limited activity or repetitive and constraining, it may



give rise to boredom. The affective component describes the subjective experience which arises from the operator's interpretation of the imposed demands. This has been related to feelings of monotony, frustration, distraction, daydreaming, dissatisfaction and satisfaction, a lack of interest and fatigue. A psychophysiological description of work underload has been formalised, since the physiological arousal associated with vigilance tasks and boredom studies yielded mixed results [18], and this study further supports the perspective that decreased arousal is associated with the subjective experience of boredom.

This dimension of subjective experience is important, since it is described in both the "underload" and the "overload" hypothesis.

The "underload" accounts describe the tediousness of vigilance task as the cause for task disengagement [12], or "mindlessness" [14], which can thus hardly be defined as an attentional resource depletion. The present results, showing a marked parasympathetic increase and a subjective disengagement along the vigilance task also fit in this "underload" perspective. However, considering the large amount of available evidence in favour of this "underload" hypothesis, the question raises why authors of fairly recent work still claim to evidence support for the "overload" hypothesis. According to these authors [16], since the perceived mental workload of vigilance task is substantial, as indicated by high scores on the NASA Task Load Index, and since subjective feedback of participants indicate they feel less energetic, more strained, bored and drowsy by the end of the monitoring task, the decrement should reflect a depletion of information-processing resources. Even if these results, showing caffeine intake enhances subjects' performance, are more consistent with the underarousal hypothesis, the authors [16] re-interpret this finding as showing that arousal increases the availability of information-processing resources, and thus that "caffeine acts as an agent that facilitates the production of resources required to sustain a consistently high level of signal detection over time". Other authors [4] again considered that, since subjective workload and stress scores after a vigilance task were high, this was sufficient to dismiss the "underload" view and to claim vigilance decrements to be due to lack of effortful attention.

However, the subjective reports on which these previous studies base their interpretation of the vigilance decrement can be intuitively predicted when comparing the description of the cognitive and affective component of the boredom model [35]. Whereas the features of the cognitive component suggest a lower physiological activation with increasing boredom or decreasing workload, the affective component might be experienced as frustration, causing a certain amount of stress, which would not be indicated by a lower activation state. Therefore, if the cognitive component prevails in the subjects' experience, underarousal will probably be measured. On the contrary, if the affective component of frustration prevails, this might be measured by an increase in physiological activation. This could be an interesting distinction to make in further research.

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