Mental and physical effort affect vigilance differently

Annika S. Smit, Paul A.T.M. Eling, Maria T. Hopman, Anton M.L. Coenen

Abstract

Both physical and mental effort are thought to affect vigilance. Mental effort is known for its vigilance declining effects, but the effects of physical effort are less clear. This study investigated whether these two forms of effort affect the EEG and subjective alertness differently. Participants performed a physical task and were subsequently presented with a mental task, or vice versa. Mental effort decreased subjective alertness and increased theta power in the EEG. Both results suggest a vigilance decline. Physical effort, however, increased subjective alertness and alpha and beta1 power in the EEG. These findings point towards an increase in vigilance. Beta2 power was reduced after physical effort, which may reflect a decrease in active cognitive processing. No transfer effects were found between the effort conditions, suggesting that the effects of mental and physical effort are distinct. It is concluded that mental effort decreases vigilance, whereas physical effort increases vigilance without improving subsequent task performance.

Keywords: Vigilance; Mental; Physical; EEG; FFT; Theta; Alpha
mental task. The enhanced theta power probably reflects a drop in vigilance. This drop might be caused by sustaining task performance, which is considered to be resource-consuming or capacity-demanding (Parasuraman, 1985; Wickens, 1984).

Vigilance effects of physical exercise have been studied less extensively, even though it is known that physical exercise affects an individual’s condition. Effects have been reported on body temperature (Nielsen and Nybo, 2003), heart rate (Dosseville et al., 2002) and on monoamine neurotransmitter systems, serotonin in particular (Gandevia, 2001; Meeusen and De Meirleir, 1995; Strüder and Weicker, 2001).

The EEG effects of physical exercise that have been reported concern an increase in alpha and sometimes theta power (Kubitz and Pothakos, 1997; Youngstedt et al., 1993). The effects of physical effort on behavioral performance are not clear. Studies have reported no effects (Tsorbatzoudis et al., 1998), negative effects (Kubitz and Pothakos, 1997), positive effects (Adam et al., 1997; Verger et al., 1998), negative effects in chronically fatigued persons (Blackwood et al., 1998), and positive effects after mild exercise, but negative effects after strenuous exercise (Féry et al., 1997). It appears that physical effort may affect performance positively, yet if sustained until sheer exhaustion, physical effort may decrease vigilance. In sum, physical effort seems to increase alpha power and positively affect performance, suggesting that physical effort might have activating effects. Increased activation after physical effort has indeed been found with subjective measures (Kubitz and Pothakos, 1997; Matsumoto et al., 2002).

Mental effort appears to decrease vigilance, whereas physical exercise seems to have activating effects. However, physical exercise has not been studied extensively and different measures of vigilance have not often been compared. In this experiment we directly compare physical and mental effort effects on both physiological (EEG) and subjective measures. Mental effort is expected to increase theta power in the EEG and lower subjective alertness. We predict that physical effort increases alpha power in the EEG. If physical effort indeed is activating, subjective alertness should increase. Moreover, we used a within-subject design that allows investigation of possible transfer effects between conditions. If the effects of physical and mental effort are indeed distinct, there may be no signs of transfer when physical and mental tasks are presented consecutively.

1. Method

1.1. Participants

Participants were 44 healthy students (8 men and 36 women; mean age 22 years). They signed an informed consent and received 20 or fulfilled a course requirement.

1.2. Recording

Electrodes were placed at Fz, Cz, and Pz (Jasper, 1958). EEG was registered with Ag–Cl electrodes in an elastic cap. The ground electrode was placed on the forehead and the left mastoid served as reference. Electro-ocular activity was recorded next to and above the right eye. Electrode impedance was less than 5 kΩ. Signals were band-pass filtered between 0.016 Hz and 100 Hz and recorded digitally (512 Hz sample frequency). The EEG was checked off-line for artifacts. Epochs were rejected for analysis if the following criteria were met with respect to the EOG: exceeding variances of 45 μV within 150 ms, and voltage steps in consecutive samples of above 25 μV. The spectral content of the EEG was determined by Fast Fourier Transformations (FFTs; frequency resolution of 1 Hz) with Hanning correction. For each EEG measurement, the spectral content was computed for 90 epochs of 2 s. Subsequently, one grand average was made of the 90 spectral power values. We distinguished five frequency bands: delta (0–3 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta1 (13–22 Hz), and beta2 (23–30 Hz). Power within bands was averaged. The EEG was always recorded during passive wakefulness, 3 min with eyes open and 3 min with eyes closed. Thus, for each measurement two average power values over 3-min (=90 epochs) periods were computed: one for eyes open and one for eyes closed.

1.3. Design and procedure

The experiment lasted from 9.00 a.m. until 12.30 p.m. Participants were randomly divided into three groups: 1, 2, and 3. The first group was subjected to mental task then to the physical task. In group 2, the order was reversed. Group 3 served as control group. First, the EEG was measured with eyes closed (3 min) and eyes open (3 min). The order of closed and open was counterbalanced across participants. Subsequently, the Thayer alertness scale was presented. This was followed by 40 min of exercise on a cycle ergometer in group 1 and by 40 min of demanding mental task performance in group 2. In the control group, participants spent 40 min talking to the experimenter and reading magazines. They joined the experimenter for a short walk (about 3 min) around the lab during this time. After the manipulation (or control condition), the EEG was measured again. Next, the Thayer alertness scale and the NASA-TLX (task load index) were presented. Then the demanding task followed in group 1, and physical exercise in group 2. In the control group, participants again conversed with the experimenter, read magazines and went for a short walk. All measurements were then repeated.

Heart rate (beats per minute) was measured during all tasks (mental and physical) for the entire 40-min period. This was done in order to check whether heart rate would be high (above 120 beats per minute) and would increase in the physical effort condition.
1.4. Materials and stimulus presentation

1.4.1. Subjective vigilance measures

Subjective alertness was measured by a paper-and-pencil version of Thayer’s subjective alertness scale (Thayer, 1978). This scale entails four factors: general deactivation, sleep, high activation (ha), and general deactivation. Together, the factors are assumed to reflect the subjective state of alertness.

The NASA-TLX (task load index) was used to measure perceived workload (Hart and Staveland, 1988). The index entails six dimensions that together represent perceived workload: mental demand, physical demand, temporal demand, performance, frustration, and effort.

1.4.2. Manipulation: mental effort, high demanding task

The demanding task of a previous experiment was used (Smit et al., 2004b). Two types of visual stimuli were presented in the task: letters (a–z) and grey squares (width: 100 pixels, height: 100 pixels), which were presented 2 cm below the letters. The letters (Arial font, size 24) appeared one by one, together with the squares, and were black against a grey background. Stimulus duration was 200 ms, the inter stimulus interval (ISI) was 800 ms for both letters and squares. Subjects were asked to push a button with their preferred index finger on every occasion the target square appeared. The target square was slightly darker than the nontarget square. The targets (dark grey square) and target sequences (x–a) were all presented 80 times during the task in a quasi-random pre-fixed order. Participants were instructed to perform as fast and as accurately as possible and to give equal weight to both tasks. Total duration of the task was 40 min.

1.4.3. Manipulation: physical effort, racing

Participants were asked to exercise on a cycle ergometer for 40 min (with 60 rotations per minute, using a metronome). The first 10 min served as warm-up and the last 5 min as cool-down: The resistance was set at 75 W at the start of the exercise and increased with 25 W every minute, until heart rate was between 130 and 150 beats per minute for each participant, indicating moderate to strenuous effort. During the period of cool down, the resistance was again set at 75 W. The Borg scale (Borg, 1982) was used as an indication of perceived physical load. The scale ranges from 0 (not enduring) to 10 (very, very enduring) and has been used in many studies (see e.g. Adam et al., 1997; Nielsen and Nybo, 2003). The scale was administered after 15, 25 and 35 min of exercise.

2. Results

Data were analyzed with repeated measures ANOVAs with Bonferroni’s confidence interval adjustments. EEG data were analyzed per electrode site with 3 × 3 × 2 (Group × Time × Eyes situation: open or closed) ANOVAs. In case of an occasional missing value for the EEG data the missing value was replaced by its group mean (there was less than 1 missing data point per participant per electrode site over the entire experiment). Performance and HR data of each measurement were split in two (part 1 and part 2) to analyze potential decrements. Heart rate scores were analyzed with a 2 × 2 (Group × Task × Part) ANOVA. Vigilance task data were analyzed with a 2 × 2 × 2 (Group × Task × Part) ANOVA. Subjective alertness scores and NASA-TLX scores were analyzed per dimension, with a 3 × 3 (Group × Time) ANOVA.

2.1. Effects on physiology

2.1.1. EEG: relative power

As there was a significant increase in total power in both experimental groups, and since relative power data yielded the most pronounced results, only relative power results are presented. There were Group × Time interactions (see Table 1); results of post hoc ANOVAs are summarized in this paragraph. Theta power in the control group was greater at time 1 than at time 3 (p = 0.114 at Fz with eyes open) and greater at time 2 than at time 3 (p = 0.047 at Pz with eyes open). There was a small trend towards an increase in theta power after mental effort.

A main Time effect was found for alpha power at Fz with eyes open, F(2.82) = 3.20; p = 0.046: there was less alpha power at baseline than at time 2 (p = 0.016). Additional tests revealed that there was more alpha power at time 2 than at baseline in group 2 (p = 0.034 at Fz with eyes open), suggesting an alpha power increase after physical effort.

For the beta1 band, post hoc tests showed that in group 1, power was greater at time 3 than at baseline (p = 0.029 at Pz

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Group × Time interaction effects relative power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eyes closed</td>
</tr>
<tr>
<td>Theta</td>
<td>–</td>
</tr>
<tr>
<td>Alpha</td>
<td>–</td>
</tr>
<tr>
<td>Beta1</td>
<td>F = 2.36; p = 0.060</td>
</tr>
<tr>
<td>Beta2</td>
<td>–</td>
</tr>
</tbody>
</table>

* F(4,82) for all F’s.
with eyes closed). In group 2, beta1 power tended to be smaller at time 3 than at baseline (p = 0.072 at Fz with eyes closed) and time 2 (p = 0.063). These results suggest that beta1 power is increased after physical and decreased after mental effort.

For the beta2 band, main Time effects were found if eyes were open: F(2,82) = 3.54; p = 0.033 at Fz: beta2 power was smaller at time 2 than at baseline (p = 0.019) and F(2,82) = 4.98; p = 0.009 at Pz: beta2 power was smaller at time 2 than at baseline (p = 0.024). Additional tests showed that beta2 power tended to be smaller at time 3 than at baseline in group 1 (p = 0.110 at Fz with eyes open). In group 2, beta2 power was smaller at time 2 than at baseline at Fz if eyes were open (p = 0.037), but there tended to be more beta2 power at time 2 than at baseline at Pz if eyes were open (p = 0.055).

The results on relative power suggest that the mental effort and physical effort conditions caused differential changes in power. To test this, 2 × 2 (Group × Condition) ANOVAs were done. For this purpose, the data of the experimental groups were divided into three segments: baseline (time 1) condition, mental effort condition and physical effort condition. In this way, the factor Time was left out and replaced by the factor Condition.

2.1.2. EEG relative power per condition

There were condition effects on relative power in the theta, alpha, beta1, and beta2 band (see Table 2). For the theta band, power was greater after mental effort than after physical effort and tended to be greater than after baseline (see Fig. 1). For the alpha band, power was shown to be greater after physical effort than at baseline (see Fig. 2). With respect to beta1 power, there was more power after physical effort than after mental effort and than at baseline. For the beta2 band, power was greater after mental effort than after physical effort and power was greater at baseline than after physical effort.

2.1.3. Heart rate (HR)

Mean HR (see Table 3) was higher in the physical than mental effort task, F(1,18)= 756.43; p < 0.001 and increased in the second part of both tasks, F(1,18)= 45.88; p < 0.001.
Mental demand

Physical effort 128 143
Mental effort 71 78

Moreover, the increase in the physical effort condition was greater than in the mental effort condition, $F(1,18)=7.95; p=0.011$.

2.1.4. Borg scale

The average score was 4.4 ("somewhat more enduring"—"enduring"). In the third 10-min block of racing (just before the cool-down), the average score was 5.4 ("enduring"—"very enduring"). There was no effect of the order of conditions.

2.2. Effects on behavioral performance

2.2.1. Mental task data

There were more misses in the second than in the first part of the task, $F(1,27)=5.94; p=0.022$. There tended to be more misses in the letter than square task, $F(1,27)=3.47; p=0.073$. A Part $\times$ Task interaction was found, $F(1,27)=17.63; p<0.001$. Additional analyses showed that in the square task, more targets were missed in the second than first part, $F(1,27)=10.52; p=0.003$. No effects were found on false alarms and errors.

RTs were longer in the square than in the letter task, $F(1,25)=216.49; p<0.001$ and longer in the second than in the first part of the tasks, $F(1,25)=16.64; p<0.001$. There was a Task $\times$ Part interaction, $F(1,25)=11.35; p=0.002$. Post hoc analyses showed that RTs were longer in the second than in the first part of the letter task, $F(1,26)=57.91; p<0.001$. No effects were found on the order of conditions.

2.3. Effects on subjective scores

2.3.1. Thayer alertness scale

Effects were only found on the factors sleep (sl) and general activation (ga). A Group $\times$ Time interaction was present for sl, $F(4,82)=10.92; p<0.001$. Post hoc tests showed that at time 2, sl in group 2 was higher than in group 3 ($p=0.004$) and the control group ($p=0.038$). At time 3, sl in group 3 was higher than in group 2 ($p=0.002$) and the control group ($p=0.047$). These results point out that sl increased after mental effort.

There was a Group $\times$ Time interaction for ga, $F(4,82)=17.23; p<0.001$. Post hoc analyses showed that at time 2, there were higher ga scores in group 3 than in group 2 ($p=0.005$). At time 2 ga scores were higher in group 2 than in the control group ($p=0.036$) and group 3 ($p<0.001$); ga scores tended to be higher in the control group than in group 3 ($p=0.093$). In summary, ga increased after physical effort and tended to decrease after mental effort.

2.3.2. NASA-TLX

There were various Group $\times$ Time interactions (see Table 4). Together, the results suggest that mental effort increased mental demand, temporal demand, and frustration scores. Physical effort increased physical demand and performance scores. There was no Group $\times$ Time interaction on the total score. The total score was lower in the control group than in group 2 ($p<0.001$) and group 3 ($p<0.001$). Groups 2 and 3 did not differ.

3. Discussion

Any mental task that requires a response entails a physical component. Moreover, it is known that physical exercise concerns a central element as well (Gandevia, 2001; Nielsen and Nybo, 2003). However, we argue that a sustained mental task condition in which relatively little muscular movement is needed, will primarily require a vast amount of central energy expenditure. Conversely, a physical effort task will lead to far more peripheral energy costs if it predominantly requires body movements that are produced by the skeletal muscles (Bouchard et al., 1993).

HR, Borg Scale scores, and TLX-physical demand scores were all high and increased during exercise. These scores are comparable to post-exercise scores that have been

Table 3
Mean HR (beats per minute) per condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>First part of task (S.E.M.)*</th>
<th>Second part of task (S.E.M.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental effort</td>
<td>71</td>
<td>78</td>
</tr>
<tr>
<td>Physical effort</td>
<td>128</td>
<td>143</td>
</tr>
</tbody>
</table>

* S.E.M.: standard error of the mean.

Table 4
Group $\times$ Time interactions on dimensions of the NASA-TLX

<table>
<thead>
<tr>
<th>TLX-dimension</th>
<th>Group $\times$ Time interaction $F(2,41)$; $p$-value</th>
<th>Main effects within groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mental demand</td>
<td>$F=58.53; p&lt;0.001$</td>
<td>Time 2: group 2$\geq$ group 3 ($p&lt;0.001$); group 3$&lt;control$ ($p=0.030$)</td>
</tr>
<tr>
<td>Physical demand</td>
<td>$F=30.58; p&lt;0.001$</td>
<td>Time 3: group 3$&gt;group2$ ($p&lt;0.001$); group 3$&lt;control$ ($p&lt;0.001$); group 2$&lt;control$ ($p&lt;0.001$)</td>
</tr>
<tr>
<td>Temporal demand</td>
<td>$F=5.84; p=0.006$</td>
<td>Time 2: group 2$&gt;group2$ ($p=0.002$); group$&gt;control$ ($p&lt;0.001$)</td>
</tr>
<tr>
<td>Performance</td>
<td>$F=3.96; p=0.027$</td>
<td>Time 2: group 2$&gt;group3$ ($p=0.095$); group 2$&gt;control$ ($p=0.014$)</td>
</tr>
<tr>
<td>Frustration</td>
<td>$F=4.8; p=0.013$</td>
<td>Time 3: group 2$&gt;group3$ ($p=0.078$); group 2$&lt;control$ ($p=0.056$)</td>
</tr>
<tr>
<td>Effort</td>
<td>$-$</td>
<td>Time 3: group 3$&gt;group2$ ($p&lt;0.001$); group 3$&lt;control$ ($p=0.039$)</td>
</tr>
</tbody>
</table>
reported by others and indicate that the exercise was moderate to strenuous (Adam et al., 1997; Féry et al., 1997; Verger et al., 1998). Participants said they felt tired after exercise, yet the Thayer scores revealed an increase in activation. Together, these results indicate that the Thayer scale might apply to feelings of mental fatigue rather than physical fatigue. Physical fatigue might concern a distinct aspect of alertness, which may not be assessed adequately by the Thayer scale. This would also imply a distinction between subjective physical and mental tiredness and supports our prediction that mental and physical effort affect vigilance differentially.

The mental effort condition was arduous as well: performance decreased, HR increased and the scores on TLX-mental demand and sleepiness increased due to the mental task. The absence of a difference in total score on the TLX after mental and physical effort indicates that there was no difference in perceived task load between the mental task and physical task.

Mental effort increased theta power, which has been found in previous studies as well (Ballard, 1996; Paus et al., 1997; Pennenkamp et al., 1994). More specifically, the theta increase on the Fz midline electrode has been reported before (see e.g. Smit et al., 2004b). An increase in theta power is considered to reflect a decline in vigilance (Coenen, 1995; Kubitz and Pothakos, 1997). Physical effort enhanced alpha and beta1 power and reduced beta2 power. The decrease in beta2 power may reflect a decrease in active mental processing directly following the exercise. An increase in alpha power has been reported after physical exercise (Kubitz and Pothakos, 1997; Youngstedt et al., 1993). This effect may reflect an increase in the input of information (Klimesch, 1999). The combination of enhanced alpha and beta1 power suggests that physical effort leads to a global activation (Kubitz and Pothakos, 1997), which is also reflected in this study in an increase in subjective activation. Activational effects after physical exercise have been found by others (Bonnet and Arand, 1997). In particular, it has been reported that physical exertion boosts monoaminergic neurotransmitter systems (Gandevia, 2001; Meeusen and De Meirleir, 1995; Peyrin et al., 1987; Strüder and Weicker, 2001), which are known to affect cortical firing and thus the EEG (Kahkonen and Ahveinen, 2002).

It is remarkable that physical effort was moderately strenuous and increased vigilance, but did not improve performance on a subsequent mental task. Other studies have reported both positive and negative transfer effects on performance (Adam et al., 1997; Blackwood et al., 1998; Féry et al., 1997; Verger et al., 1998). However, a lack of behavioral effects after physical effort has been reported before (Tsorbatzoudis et al., 1998) and Matsumoto et al. (2002) also found the combination of subjective activating effects without behavioral effects. These findings on the one hand indicate that performance is only decreased after great exhaustion; on the other hand the results suggest that task performance does not necessarily increase as a consequence of a higher level of vigilance.

Possibly, an increase in vigilance after physical effort is distinct from a condition of increased vigilance that is required for better behavioral performance. Although it has been acknowledged in the physiological literature that exercise has central effects (see e.g. Gandevia, 2001), it has remained uncertain to what extent and in what direction the central nervous system is affected. In psychological research, a distinction has been made between arousal and capacity (Kahneman, 1973): arousal in this context can be used interchangeably with vigilance and forms the basic energetic level of a person, whereas capacity is synonymous with resources, which refers to attention and is momentarily allocated to ongoing processes. It might be that physical effort enhances arousal, but does not easily affect the amount of resources or capacity that can be allocated during task performance. Kahneman (1973) could not specify what the physiological mechanisms were for capacity. However, we suggest that spectral power in the EEG in the frontal lobes may reflect the allocation of resources or capacity. Higher cognitive functions such as allocation of attention, is likely to take place in the frontal lobes: this is exactly the part of the brain that did not show an increase in beta1 power after physical effort in this study. More specifically, at Fz beta2 power was decreased, indicating lowered cortical activity. We suggest that physical effort increases the general level of vigilance, but does not upgrade cortical firing that is specifically related to allocation of resources to ongoing processing. Therefore, behavioral performance is not easily affected.

We conclude that mental and physical effort affect vigilance differently, as EEG effects and effects on subjective alertness differed between the effort conditions. This conclusion is in line with suggestions (Dodge, 1917) and results (Fibiger and Singer, 1989) of others. It is strengthened by the absence of transfer effects between tasks: the effects of mental and physical effort did not interact. Mental effort lowers vigilance, whereas physical effort increases vigilance without necessarily improving subsequent task performance.

Acknowledgements

We would like to thank Anneke Mol and Peter Staal for their assistance during the experiment. We are grateful for the general technical guidance of Willy van Schaik and Jos Wittebrood. We thank Hubert Voogd for constructing software for the mental effort task and Philip van den Broek for support with respect to EEG analyses.

References


Mosso, A., 1894. La Fatigue Intellectuelle et Physique. Ancienne Librairie Germer Bailli`ere, Paris (translation from Italian).


