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Abstract

There are only a few studies using human electroencephalograms (EEGs) to investigate bioelectrical changes in the brain during exercise (running or cycling). These studies report an increase in EEG alpha amplitude during and immediately after exercise. However, only exercises within a relatively short time interval of approximately 1 hour have been investigated. Thus, we focussed on long-lasting exercise and report three single case studies, performed on the same participant, during extended exercise and under different thermal conditions. EEG was recorded during a 12-, 24-, and 56-hour ultramarathon. The 56-hour race was performed under extreme thermal stress in Death Valley, CA, with temperatures well above 55°C/131°F. Analyzing the centre gravity frequency of the EEG alpha rhythm yielded a gradual decrease with time for the 12- and 24-hour races. In the 56-hour race, the centre frequency decreased only until the first sleeping period. Alpha amplitude, on the other hand, did not vary systematically. For all three races, the lowest alpha amplitude was observed during the last test session. This decrease is most likely due to cognitive and emotional changes but not to thermal stress, exhaustion, or sleep deprivation.

Keywords: EEG, alpha, running, ultramarathon, Badwater, thermal stress, sleep deprivation, centre frequency

Introduction

Long-lasting sports activity exerts differential effects on the human body, including a variety of biochemical and haematological parameters (Von Duvillard, Braun, Markofski, Beneke, & Leithauser, 2004; Wu et al., 2004; Yusof et al., 2007), as well as cognitive performance (see Tomporowski, 2003, for a review). Although, according to Tomporowski (2003), in many studies focussing on longer-lasting exercise (up to 1 hour) attentional and problem-solving processes were improved, those types of exercises, which lead to a depletion of physiological energy stores, lead to a reduction in cognitive performance.

Although performance in exercise and competition is strongly dependent on processes within the central neural system, only few reports address bioelectrical changes in the brain. While most studies, focussing on exercise and electroencephalogram (EEG), report data of relatively short exercise durations, this report concentrates on longer-lasting, enduring exercise. In three single case studies, performed on the same subject, we investigated the changes in EEG during a 12-, 24-, and 56-hour (Badwater Ultramarathon) footrace, the latter with ambient temperatures of up to 55°C/131°F.

Although the whole EEG spectrum includes a series of different frequency bands as delta (1–4 Hz), theta (4–8 Hz), beta (12–25 Hz), and many others, the most prominent rhythm, visible in human EEG, is the alpha rhythm, an oscillation in the frequency range of 8–12 Hz. Besides a variety of different methodological approaches, here two different parameters of the EEG were analysed: (a) the magnitude of EEG amplitude given as average amplitude in microvolts and (b) the frequency of

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the EEG signal, indicating the speed of the dominant oscillation – termed centre frequency of the alpha rhythm. In general, a decrease in the alpha amplitude can be interpreted as cortical activation, whereas an increase indicates deactivation (Doppelmayr et al., 2005; Klimesch, 1999; Sauseng et al., 2005). On the other hand, analysing the centre frequency of the alpha rhythm, it has been demonstrated that alpha frequency is related to cognitive performance in a way that subjects with higher (i.e., faster) alpha frequencies had better memory performance or higher intelligence (Clark et al., 2004; Doppelmayr, Klimesch, Stadler, Pöllhuber, & Heine, 2002; Klimesch, 1997; Klimesch, Schimke, & Pfurtscheller, 1993). These results indicate that cognitive performance is related to both frequency and amplitude of the alpha rhythm.

With respect to exercise, the EEG frequency spectrum has been investigated by several authors (for a review see Crabbe & Dishman, 2004, or Mechau, 2001), most of them reporting an increase of alpha amplitude during exercise, at least during shorter bouts of exercise, not exceeding 1 or 2 hours (Boutcher & Landers, 1988; Kamp & Troost, 1978; Petruzello & Landers, 1994; Pineda & Adkisson, 1961; Wiese, Singh, & Yeudall, 1983; Youngstedt, Dishman, Cureton, & Peacock, 1993). As outlined earlier, an increase in alpha amplitude indicates deactivation; thus these findings have been interpreted in terms of decreased cortical activity. So far no studies focussed on alpha centre frequency during exercise.

In the Badwater Ultramarathon, thermal stress is a relevant factor; thus EEG changes related to temperature have to be taken into account. Nielsen, Hyldig, Bidstrup, González-Alonso, and Christoffersen (2001) focussed on the effect of thermal stress on EEG during prolonged exercise in heat. The results, as measured by changes in the ratio of alpha/beta power, an indicator for suppressed arousal, yielded a significant correlation with oesophargengal temperature, indicating an elevated alpha/beta ratio in the hot environment (suppressed arousal). Similar results have been reported by Cheung and Sleivert (2004).

All studies performed using human EEG, with respect to sports and exercise in normal or hot environments, comprised only relatively short time intervals (Cheung & Sleivert, 2004; Hocking, Silberstein, Lau, Stough, & Roberts, 2001; Nielsen et al., 2001). However, the studies included in this report lasted much longer, namely 12, 24, and 56 hours. Specifically for the 24- and 56-hour races, sleep deprivation might be an additional factor that has to be taken into account. Hori, Hayashi, & Morikawa (1994) investigated the transition from wakefulness to sleep and divided nine different stages with a decreasing amount of alpha amplitude when the subjects fell asleep. In those stages (1 and 2) rated as awake, alpha was present in at least 50%. Strijkstra, Beersma, Drayer, Halbesma, and Daan (2003) investigated the effect of sleep deprivation on human EEG and reported a shift of centre frequency to lower frequencies indicated by a decrease in alpha and an increase in theta (4–8 Hz) amplitude.

The interesting question, therefore, is whether the findings reported for short exercises will be valid also for long-lasting, enduring sports events. We present three single case studies: a 24-hour run, the Badwater Ultramarathon (56 hours under thermal stress), and a 12-hour run. With respect to alpha frequency, we expect a slow decrease throughout each of the respective races according to a decrease in cognitive performance, as reported for long-lasting exercises (Doppelmayr, Finkernagel, & Doppelmayr, 2005; Tomporowski, 2003). Although short exercise leads to an increase in cortical activation (alpha amplitude reduction), long-lasting physical activity should lead to a slow decrease in cortical activity; thus an increase in alpha amplitude was expected. Additionally, under thermal stress, as given in the Badwater race (more than 50°C ambient temperature), a reduction in the alpha/beta amplitude ratio was expected.

Materials and Methods

Subject

One male subject, age 42 years, voluntarily participated in these experiments. Participation, especially in the Badwater Ultramarathon, is, as described by the race director, a severe physical risk (including dehydration, heat cramps, heat stroke, hypoanthermia); thus one of the authors, well informed about all risk factors, served as the subject. Furthermore, the subject decided to participate in these races (except the 12-hour race) before the study was designed.

Races and recordings

The first race, a 24-hour ultramarathon, took place on a flat 2-km round course, and he finished after 24 hours, having run 125 km. Electrodes were placed along the midline of the head at frontal (Fz), central (Cz), parietal (Pz), and occipital positions according to the international 10–20 system for electrode positioning. Data were recorded using a Neuroscan Synamps amplifier, mounted in the medical service station. Electrodes were applied approximately every third hour (Table 1), and EEG was recorded for 1 minute with eyes closed, while the subject sat quietly on a chair.

The second race reported is the Badwater Ultramarathon (for a detailed description see http://www.badwater.com). The race, known as one of the most difficult footraces, comprises a length of 215 km leading from Badwater (Death Valley National Park, CA), at 80 m below sea level, to the Mount Withney Portal (finish at 2,500 m above sea level). Temperatures ranged from 55°C/131°F at noon on the first day to 13°C/55°F during the second night. After a collapse at 18 hours, the participant took a

Table 1

24-Hour race – 24-Stunden-Lauf Klopein											
Measure	BL	1	2	3	4	5	6	7	8	9	10
Time of Day	11	14	16	19	21	24	02	04	07	09	11
Hours Raced	0	2	4	7	9	12	14	16	19	21	23
Kilometres finished	0	18	33	49	59	76	86	93	100	111	121
56-Hour race – Badwater Ultramarathon											
Measure	BL	1	2	3	4	5	6	7			
Time of Day	17	11	15	23	6	12	19	6			
Hours Raced	0	3	7	15	22	28	35	46			
Kilometres finished	0	20	46	67	80	104	133	170			
Temperature in °C	51	53	55	44	32	45	31	36			
12-Hour race – 12-hour Comparison											
Measure	BL	1	2	3	4	5	6	7	8	9	
Time of Day	14	14.75	17	18	19.75	21	22	23.75	1	2.5	
Hours Raced	0	0.75	3	4	5.75	7	8	9.75	11	12.5	
Kilometres finished	0	6	14	20	27	34	40	47	54	60	

In Table 1, exact time points for kilometres and temperature values (for the Badwater race) for the test sessions during the races are given (BL = baseline).

sleeping break of 4 hours. Additionally, there were approximately five short resting breaks without sleep and four short naps of approximately 10 to 30 minutes on Day 2, and he finished after 56 hours. Throughout the race the subject carried a Varioport EEG system with 10 electrodes at left and right frontal (F3, F4), central (C3, C4), parietal (P3, P4), and occipital (O1, O2) areas. Due to artefacts, many channels had to be excluded and only P4 (right parietal position) was reported. To reduce time loss in the experiment, seven test sessions were accomplished while the subject walked slowly with eyes closed, hand held by one member of the support crew. Points of time of EEG sessions and temperature are listed in Table 1. In a pretest we compared the EEG between walking and sitting, both with eyes closed, and found only marginal, nonsignificant differences at very low frequencies (below 4 Hz). The reason to use the walking EEG in this experiment was twofold. First, to reduce time loss; and second, more importantly, to keep the subject going at his or her own pace. It is very difficult for the participant to stop, sit down, and start again, if he is completely exhausted and the feet are covered with large blisters.

The third race was a 24-hour ultramarathon and was performed for comparison reasons only. Due to a knee injury, the race, which had been planned as a 24-hour run, had to be stopped after 12 hours. The subject stated at Kilometre 52 that he would stop the race after the end of the third round at Kilometre 60. Because the injury was not very painful, no negative effects on EEG could be expected. Ten test sessions (see Table 1) comprising 1 minute resting EEG with eyes closed were recorded while sitting inside a car. Again the Varioport system had been in use and only Pz could be reported.

EEG quantification

After visual inspection and artefact rejection, power-spectra and centre frequency (representing mean alpha frequency) of the alpha band (8-12 Hz) was calculated for all 1-minute periods. All amplitude spectra were calculated with a 1-Hz frequency resolution using BrainProducts (Germany) Brain Vision Analyzer software. Frequency bands were averaged for theta (4–8 Hz), lower alpha (8–10 Hz), upper alpha (10–12 Hz), beta 1 (12–18 Hz), and beta 2 (18–25 Hz). Additionally, the alpha/beta ratio was calculated using the formula alpha/beta1.

Although three slightly different resting conditions were used (eyes closed either sitting in the medical tent or in a car, and walking with eyes closed), we assumed that it was justified to compare the data sets for the following reasons. Neither the calculation of alpha centre frequency nor alpha amplitude is affected by movement artefacts that might occur in lower or higher frequency ranges. Although selective movement of hands or feet can change cortical rhythms as mu, beta, or gamma (Pfurtscheller & Lopes da Silva, 1999), these changes are limited to movement-related cortical areas, but not detected at parietal leads (as used in this study). Furthermore, the origin of these electrical signals is hidden in the fissura longitudinalis and thus difficult to detect with EEG. Finally, statistical analyses of EEG data were performed within the same condition only; thus, even if movement-related effects could have been included in the respective signals, the amount of this movement would remain the same within each race.

Results

For each race Spearman rank correlations were computed between alpha centre frequency and the time the subject was in the race. A decrease in centre frequency indicates a slowing of the EEG signal within the alpha frequency band. The correlation between time and centre frequency yielded two significant results. For the 12-hour race (rho $= -0.636$, $p = 0.048$, $n = 10$) and for the 24-hour race (rho $= -0.727$, $p = 0.011$, $n = 11$), a significant

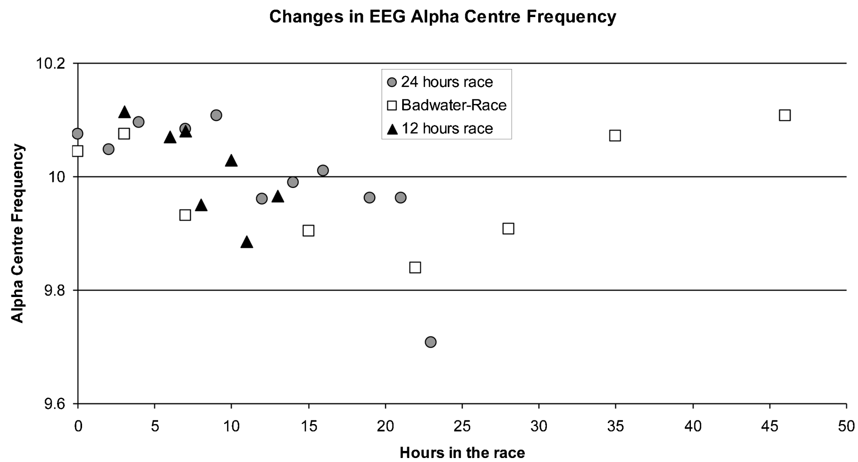

Figure 1. Changes in EEG alpha centre frequency. Changes in EEG alpha frequency for the 12-hour (black triangle), 24-hour (grey circle), and 56-hour races (white squares) are depicted. Although for the 12- and 24-hour race the centre frequency gradually decreases, this holds true for the 56-hour race only during the first 24 hours. The increase for the 56-hour race on Day 2 is due to short naps and a generally better physical condition of the subject.

decrease in centre frequency was observed. As can be seen in Figure 1, a strong negative relationship between centre frequency and hours in the race can be observed for the Badwater race too, but only during the first day. If only those time intervals that were recorded before the first short sleeping period (e.g., until Measurement 5) are included in the correlation, for the Badwater Ultramarathon too, a significant decrease in gravity frequency can be observed (rho $= -0.900$, $p = 0.032$, $n = 5$).

Discussion

When interpreting these results it has to be kept in mind that this was a field study, performed on one subject only. Additionally, because of the extreme environment, especially in the Badwater race, the quality of the data does not meet the standard of a quiet acclimated laboratory setting. However, no comparable data for these extreme situations have been reported until now, and the conclusions have to be taken with care.

Analysis of these three case studies revealed two interesting findings. First, we found that the centre frequency shifts to lower frequencies with increasing time and therefore with longer exercises. This result holds true for the 12- and 24-hour races, where no sleeping periods occurred. Additionally, during the first 24 hours of the Badwater Ultramarathon, a similar effect could be observed. In general, a reduction in centre frequency can be observed during sleep deprivation. Strijkstra et al. (2003) reported a shift to lower frequencies according to subjective sleepiness, indicated by a decrease in alpha and an increase in theta power. Furthermore, the importance and effectiveness of short naps, as during the Badwater race, has been described in detail by Hayashi, Ito, and Hori (1999). These short naps might be the reason for the higher centre frequency on Day 2 and Day 3. The slowing of the centre frequency, as observed in these experiments, therefore, is well in line with these findings, as well as with an assumed reduction in cognitive performance (Tomporowsky, 2003; Doppelmayr et al., 2005).

Doppelmayr et al. (2005) reported that (at least nonelite) participants in ultralong races remain on a relatively low lactate level. Thus, we can assume that the participant remained at a nonaccumulating level. Mechau, Mücke, Weiß, and Liesen (1998), however, reported an initial increase in alpha amplitude in subjects, even when running on a nonaccumulating lactate level. Unfortunately, we could not support these findings. We have observed neither an initial increase in alpha amplitude, not even in the 12-hour study when the first EEG recording was performed after 45 minutes, nor a long-lasting elevated maximum alpha amplitude in any of the races. As outlined and in contrast to the present report, most studies only analysed considerably shorter intervals. The only long interval has been analysed by Schrode, Larbig, Heitkamp, and Wurster (1986), who recorded the EEG of 27 highly trained subjects before, during, and after a marathon and reported a reduced relative amount of EEG alpha power after the marathon.

The most robust and obvious finding with respect to alpha power was a reduction during the final assessment in each race. During these final recordings, the subject already knew either that he would be able to finish or that he had "almost done" it. For the 24-hour race the last recording was assessed 1 hour before the end of the race. During the Badwater race the last session was made already several hours before the finish; nevertheless, at this point in the race it was clear that the subject would stay within the given 60-hour cutoff. This was by no means clear after 36 hours at Kilometre 133. Finally, during the 12-hour race, the subject knew and already stated that he would quit after the ninth recording. Because the time interval for the last measure varied, depending on the overall time, between 11, 23, and 46 hours for the three races, we assume that the

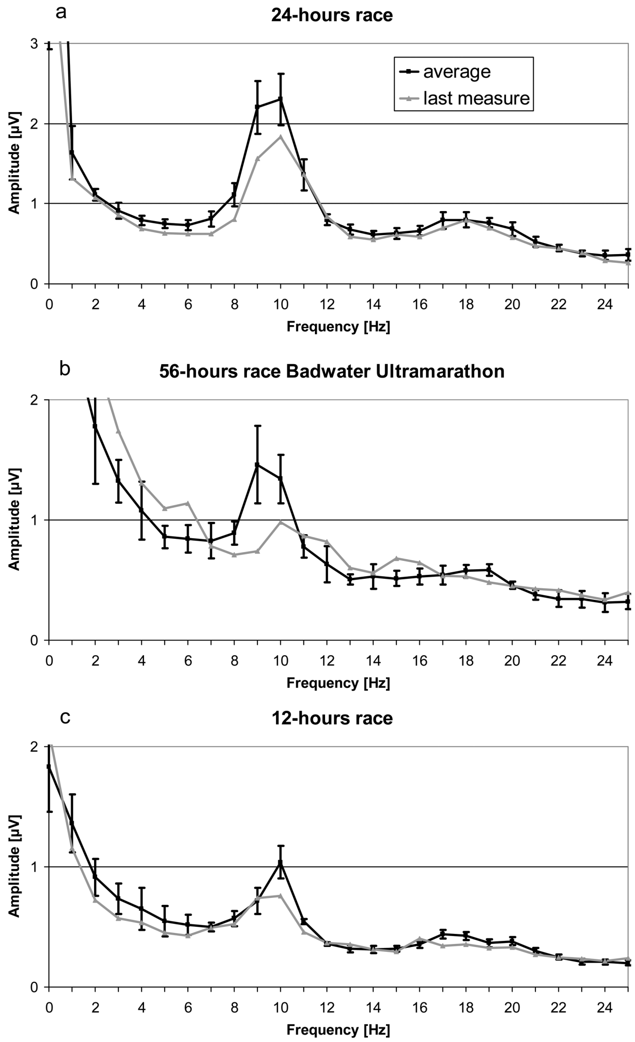

Figure 2. EEG amplitude. The average amplitude-spectra (black) +/− 2 SE and the respective last assessed spectrum for each race are depicted. For all three races, the 12-, 24-, and 56-hour race alpha amplitude in the range 8–12 Hz clearly yielded the lowest values. This reduction in amplitude is most likely due to cognitive and/or emotional activation but not to exhaustion, sleep deprivation, or exercise duration. For the 12- and 24-hour race results from the electrode site, Pz are depicted, and data from the 56-hour race were recorded at P4. Furthermore, for each frequency band and the alpha/beta ratio, Spearman rank correlations were calculated for EEG amplitude and the hours the subject was in the race, but no significant results were obtained. The means of power spectra (+/− 2 SE) with 1 Hz frequency resolution are depicted in Figure 2, a–c. No clearly detectable increase in power immediately after the onset of the sports activity could be detected, or any trend in either the positive or negative direction. While throughout the races the power of the different frequency bands varied to some degree, the only result consistently found in all three races was a decrease in alpha power during the last measure in the respective race.

decrease in alpha power, for the last assessment only, reflects cognitive and emotional arousal rather than sleep deprivation, hyperthermia, or simply exhaustion.

Contrary to our hypothesis concerning the influence of temperature, no clear evidence could be observed for a reduction in the alpha/beta ratio. Even during the Badwater race at Time Points 1 and 2, when temperatures reached 55°C and 48°C degrees, respectively, no clear and consistent changes in EEG alpha power or alpha/beta ratio were observed.

Given the extreme nature of the races included in this report, we cannot rule out the possibility that further variables such as circadian changes in the rhythms, short changes in sleepiness and attention, or nutrition and/or dehydration might have influenced the results.

In general, the data for these three studies show a slow but steady decrease in centre frequency, most likely due to sleep deprivation, as well as a decrease in alpha power in the last sections of the races. This decrease may be attributed, to a higher degree, to emotional and cognitive arousal rather than to extended exercise, temperature, dehydration, or sleep deprivation. Besides this decrease, alpha amplitude seems to be relatively insensitive to thermal stress or exhaustion due to exercise duration.

The results of this study, therefore, provided greater insight into brain oscillatory processes during exercise in extreme environments. Future studies will have to focus on recording of ongoing EEG not only at selected resting intervals but also throughout the race. This might help with assessing the mental state of athletes during long-lasting events and with planning resting or sleeping periods accordingly.

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