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Observational study of the effects of maximal oxygen uptake on cognitive function and performance during prolonged military exercise

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ABSTRACT

Introduction Military operations place high demands on many cognitive functions, and stressful events characterise the military work environment. The study aimed to examine the relationship between cardiorespiratory fitness, stress response, cognitive function and military performance during prolonged military exercise.

Methods 66 army cadets were included in the study. The subjects participated in a 4.5-day military winter training in northern Sweden. Maximal oxygen uptake (VO_2max) was estimated from a cycle test. Cognitive tests (design fluency, DF test) and measurements of heart rate variability (HRV) were conducted before and after the exercise. Assessment of military performance as an individual soldier (P-ind) and performance as a team leader (P-lead) was carried out during the final day of the exercise. Pearson's coefficient of correlation (*r*) and Spearman's rho were used to evaluate correlations, and linear regressions were used to examine the relationships between VO_2max, HRV, DF test scores and military performance. Simple mediation analyses were performed with DF test scores and military performance (P-ind, P-lead) as dependent variables, VO_2max as a predictor and HRV as a mediator.

Results Post-exercise HRV was related to military performance (P-ind: $r=0.40$, $p<0.01$; P-lead: $r=0.32$, $p<0.05$). Absolute VO_2max was positively correlated with P-ind ($r=0.28$, $p<0.05$), and the effect of VO_2max on military performance was mediated by HRV. Post-test DF scores were negatively correlated with post-exercise HRV (total correct designs: $r=-0.26$, $p<0.05$; total incorrect designs: $r=-0.27$, $p<0.05$).

Conclusions Results suggest that high absolute VO_2max predicts military performance by reducing the stress response to prolonged military exercise. Aerobic capacity may provide a meaningful effect on the ability to preserve military performance. Future studies need to identify thresholds for this capacity.

Pre-registration The protocol was retrospectively registered at OSF (https://osf.io/), registration DOI 10.17605/OSF.IO/ND6XM.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Military service entails both physical exertion and psychological stress, and modern military operations place high demands on physical fitness as well as cognitive dominance.

WHAT THIS STUDY ADDS

⇒ This study shows that military performance is influenced by cardiorespiratory fitness; those with a higher fitness level exhibit a lower stress response following prolonged military exercise.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Future studies need to identify any possible thresholds where aerobic capacity may provide a meaningful link to the ability to preserve military performance.

INTRODUCTION

Military service entails both physical exertion and psychological stress due to harsh and dangerous environments, extreme temperatures, sleep deprivation, caloric deficits and dehydration. All these factors could potentially impact cognitive function and mental health.[1 2] Stress and fatigue from prolonged physical work and heavy load carriage negatively affect military performance (eg, shooting, reaction time, decision-making and cognitive control).[3–6] Modern military operations place high demands on physical fitness as well as 'cognitive dominance' (intellectual advantage over a situation or adversary).[7] The ability to withstand stress and maintain good cognitive function during and after a specific task or workday is fundamental within a military context.

Aerobic fitness positively affects cognitive function and psychological health.[8–10] Good aerobic fitness mitigates stress reactions from extreme military training[11] and is associated with several cognitive functions during stressful military exercises.[12–14] General physical fitness predicts military performance,[15] enhances psychological resilience, cognition, mood and pain threshold,[7] and offsets stress-induced declines in cognitive function.[16] Heart rate variability (HRV) measures indicate that a reduction in fitness during 12 weeks of military training negatively influences stress and recovery.[17] HRV is a physiological measure of the variation in time between successive heartbeats. It reflects the autonomic nervous system's influence on the heart rate (HR) and the ability of the heart to adapt to changing demands. HRV can quantitively assess stress, recovery and resilience.[18 19] Previous studies have reported promising results in using HRV to monitor stress and recovery in first responders and tactical operators[18 20 21] and have identified a possible relationship between resilience factors and HRV during stress-inducing military simulations.[22] High HRV is associated with better decision-making and executive function[20 23 24] in tactical personnel,

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but the relationship between HRV and job-specific performance is not fully understood.[20]

The aim of the present study was to examine the relationships between cardiorespiratory fitness, stress response, cognitive function and military performance. The hypothesis was that VO_2max would be associated with cognitive function and military performance during prolonged military exercises. These associations were hypothesised to be stronger for more challenging cognitive tasks. Additionally, it was hypothesised that stress response would mediate these relationships.

METHODS

The study was carried out in February 2023. Subjects were recruited from a class of 76 army cadets. The cadets conducted military winter training (MWT) in Arvidsjaur, northern Sweden. The exercise lasted for 4.5 days. The temperature ranged from +4.0 and −22.0°C with wind speeds from 0.4 to 8.0 m/s. There was no noticeable precipitation. The physical activity was of low to moderate intensity. The cadets worked in groups of 17–18 persons. They walked, skied and participated in live-fire exercises and battle drills for 10–14 hours per day. In addition to that, they worked at the campsite and received education in skiing techniques and firing positions suitable for combat in subarctic environments. The basic equipment load was 10 kg and additional equipment (≤20 kg) was handled for shorter periods. The participants were of varied body sizes, ages and fitness levels and had varied experience in military operations and winter exercise. Sleep was partly compromised during the exercise. The cadets spent one night in a bivouac shelter in the snow and were allowed to rest in tents with stoves the other nights. There were no restrictions on caloric intake.

Measurements

Submaximal cycle tests were conducted for estimation of VO_2max. The Ekblom-Bak test consists of 8 min continuous cycling with 4 min at a workload of 0.5 kilopond (30 W) and 4 min at a higher work rate, individually determined for each subject. The full description of the test procedure is published elsewhere.[25] All tests were conducted by trained personnel with adequate education and knowledge about the Ekblom-Bak test procedure. Tests were performed on a manually calibrated cycle ergometer 928E (Monark Exercise AB, Vansbro, Sweden). All HR recordings were conducted with a Polar m400 heart rate monitor (Polar Electro Oy, Kempele, Finland). Values are presented in terms of absolute (L/min) and relative (mL/kg/min) VO_2max.

Measures of HRV were conducted the day before and immediately after the termination of the MWT. The HR sampling was preceded by a minimum of 5 min of rest. The recorded HR files were exported to the software POLAR Flow Sync (V.4.0.11; Polar Electro Oy, Kempele, Finland). Flow Sync Data were extracted for analysis using Kubios HRV Scientific (4.0.1; Kubios Oy, Kuopio, Finland). A 5-min period was used for HRV analysis. The ratio between SD1 (the SD of Poincaré plot perpendicular to the line-of-identity) and SD2 (the SD of the Poincaré plot along the line-of-identity) was used as a measure of HRV.

The cognitive tests were conducted the day before and immediately after the MWT. The design fluency (DF) test from The Delis-Kaplan EF System (D-KEFS) test battery assesses the ability to generate geometric patterns and is thought to reflect executive functions, cognitive flexibility and planning.[26] The test comprises three subtests (DF 1, DF 2, DF 3) with increasing complexity. For each subtest, the subjects were asked to perform as many unique designs as possible within 60 s. The DF tests were administered by three research staff members with previous experience in the administration of cognitive tests and good acquaintance with the DF test procedure.

Table 1 Characteristics of the study sample (n=66)

Variable	Men (n=56)	Women (n=10)
Age (years)	27.4 (5.76)	23.4 (3.75)
Height (cm)	182.0 (7.47)	165.0 (6.77)
Body mass (kg)	85.4 (12.0)	68.2 (6.55)
VO_2max (L/min)	4.46 (0.58)	3.14 (0.21)
VO_2max (mL/kg/min)	52.9 (7.74)	46.1 (4.66)

Values are given as means with SD.
VO2max, maximal oxygen uptake.

Military performance was assessed during the final day of the MWT. A 6-point Likert scale was used for assessment. The main instructor for the group (an officer) graded the performance of each cadet regarding individual capability and behaviour (P-ind), as well as leadership and group orientation (P-lead).

Statistical analysis

Outcome variables were HRV, DF test scores, P-ind and P-lead. Continuous descriptive characteristics were summarised as means with SD or median with IQR. The assumption of normality was tested using the Shapiro-Wilk test. Pre-MWT and post-MWT differences in HRV and DF test scores were analysed using paired sample t-tests and Wilcoxon signed-rank test, respectively. Pearson's coefficient of correlation (r) was used to evaluate the relationship between VO_2max, HRV, DF test scores and performance assessments. Spearman's rho was used to evaluate the relationship between pre-test and post-test DF scores. In multiple linear regressions, VO_2max and HRV were used as independent variables, and P-ind, P-lead and cognitive test scores were used as dependent variables. For DF test scores, residuals were normally distributed. Regression models were controlled for age, sex and body mass. Associations are reported as beta and p values for adjusted models. Simple mediation analyses were conducted with performance measurements as dependent variables, VO_2max as a predictor and HRV as a mediator. From the mediation analysis, indirect, direct and total effects were obtained. Results from the mediation analyses were reported as beta, z and p values. Additional analyses: subjects were divided into high and low fitness (low <median VO_2max, high ≥median VO_2max). A two-way repeated-measures analysis of variance (ANOVA) was performed to investigate the interaction between group (high and low fitness) and time (pre-MWT and post-MWT). Statistical significance was set at $p<0.05$ for all analyses. The statistical analyses were conducted using Jamovi (V.2.3.21).[27]

RESULTS

Subject characteristics are presented in table 1. Seven subjects (six men, one woman) chose to withdraw from the study before any post-test measurements were done, and two subjects (men) were unable to participate in the cognitive tests and measurements of HRV due to other duties. One male subject was excluded due to missing data (HRV and DF test scores). A total of 56 men and 10 women were included in the final data analysis. There were no systematic differences between dropouts and completers.

Table 2 Design fluency (DF) test scores before (pre) and after (post) military winter training

Variable	Pre	Post	Difference pre-post	Spearman's rho
DF total correct	33 (9.25)	39 (9)	***	0.74***
DF 1 correct	12 (4.0)	15.0 (4.75)	***	0.64***
DF 2 correct	11.5 (4.0)	14.0 (4.0)	***	0.66***
DF 3 correct	9.0 (3.0)	10.0 (2.0)	**	0.54***
DF total incorrect	4.0 (3.0)	6.0 (5.0)	***	0.45***
DF 1 incorrect	1.0 (2.0)	1.0 (2.0)	*	0.24
DF 2 incorrect	1.0 (2.0)	2.0 (2.0)	***	0.22
DF 3 incorrect	2.0 (2.0)	2.0 (2.0)	ns	0.31*

Values are given as median with IQR. p=Wilcoxon Signed Rank test p value of pre- and post-test scores.
*p<0.05, **p<0.01, ***p<0.001.

The median score for P-ind was 4 (2), ranging from 2 to 6. The corresponding value for P-lead was 4 (1), ranging from 1 to 6.

The total number of correct designs in the DF test increased from pre to post, and the proportion of correct designs in relation to the total number of designs was 0.89 pre-MWT and 0.87 post-MWT, respectively. The number of incorrect designs also increased from pre to post, except for incorrect DF 3 designs (table 2). The proportion of incorrect designs in relation to the total number of designs was 0.11 pre-MWT and 0.14 post-MWT, respectively.

Mean values for SD1/SD2 were 2.53 (0.84) and 2.71 (0.65) pre and post, respectively. There were no significant pre-test to post-test differences in SD1/SD2. The correlation between pre and post values was 0.35 (p=0.01).

Associations between VO_2max, HRV, cognitive function and military performance

Absolute VO_2max (L/min) and post-exercise measurements of SD1/SD2 were significantly correlated (r=0.34, p=0.01). The relationship between VO_2max, HRV, total DF test scores and performance assessments is presented in table 3 (all correlations are found in online supplemental table 1). The absolute VO_2max (L/min) was positively correlated with P-ind, and this relationship remained significant when simultaneously controlling for age and body mass. The association became non-significant when controlling for sex.

There was no relationship between VO_2max and post-test DF scores. Linear regression analysis revealed that the post-exercise SD1/SD2 was related to both P-ind and P-lead, and that these associations remained significant when simultaneously controlling for age, sex and body mass. The fully adjusted values for P-ind and P-lead were beta=0.31 (p=0.01) and beta=0.25 (p<0.05), respectively. There was a negative correlation between post-exercise SD1/SD2 and the total number of incorrect designs in the DF test, and this relationship was not explained by age, sex and body mass (beta=0.30, p<0.05). SD1/SD2 was also negatively correlated with the total number of correct designs, but this association diminished when controlling for sex. No sex-specific analyses were conducted due to the low number of female subjects.

Results from mediation analyses revealed that post-test HRV (SD1/SD2) significantly mediated the relationship between absolute VO_2max and P-ind. The indirect effect was β 0.21, z=2.01, p=0.04, and the total effect was β 0.47, z=2.56, p=0.01, respectively. Stress response (HRV) accounted for 44% of the total effect. Further exploratory analyses revealed that there was an indirect effect of VO_2max through HRV (SD1/SD2) on P-lead (β 0.22, z=2.04, p=0.04). Furthermore, there was no interaction effect between the low and high fitness groups regarding any of the DF test scores.

DISCUSSION

Absolute VO_2max was positively correlated with individual military performance, and this effect was mediated by HRV. Higher stress response negatively influenced military performance, as indicated by a significant positive relationship between the post-exercise HRV measurements and military performance assessments. None of the DF test scores were significantly correlated with VO_2max; however, there was an observable trend suggesting potential mediation through HRV on the non-significant association (p=0.07) between VO_2max and number of incorrect DF 3 designs.

Individuals with higher aerobic fitness demonstrated a lower stress response and better military performance. This is in line with previous findings that high aerobic fitness corresponds to less relative effort in weight-bearing exercises and is positively associated with the ability to successfully manage or adapt to military training.[12 13 15] The lack of significant associations between relative VO_2max (mL/kg/min) and military performance in the present study strengthens the importance of absolute VO_2max within military contexts. Military work without physical demands may still be facilitated by high relative values.[13]

Contrary to our initial hypothesis, there was no positive correlation between cardiorespiratory fitness and cognitive performance. Both correct and incorrect designs were negatively correlated with stress response in the present study, indicating an overall lower production of designs in individuals with a lower stress response. These results could be influenced by a more hypervigilant state in stressed cadets. A related finding is that military personnel under high-stress conditions fire at more

Table 3 Correlations between VO_2max, HRV (SD1/SD2), design fluency (DF) test results and military performance

	Design fluency test					
	Pre		Post		Military performance	
Variable	Total correct	Total incorrect	Total correct	Total incorrect	P-ind	P-lead
VO_2max (L/min)	0.06	−0.08	0.02	0.02	0.28*	0.18
VO_2max (mL/kg/min)	0.07	0.16	0.10	0.10	0.21	0.16
Pre HRV SD1/SD2	−0.24	−0.09	–	–	–	–
Post HRV SD1/SD2	–	–	−0.26*	−0.27*	0.40**	0.32*

Values are Pearson's or Spearman's correlations, where appropriate.
*p<0.05, **p<0.01.
HRV, heart rate variability; P-ind, individual military performance; P-lead, military leadership performance; VO2max, maximal oxygen uptake.

targets—both friend and foe.[24] However, the latter situation reflects an attempt to decrease the threat of injury and death and might not be comparable to the cognitive task in the present study.

The DF tests were used to assess cognitive functions that are believed to be important for most military personnel; executive functions, cognitive flexibility and planning.[26] The first two tasks in the test series rely on motor planning, and the switching component of the third task (switching between black and white dots) captures the ability for visual scanning and perhaps visual-attentional resources. It has been shown that cognitive flexibility seems to be a less important contributor to the DF test performance.[28] The expected increase in correct DF test scores between baseline and re-test is approximately 15% due to the loss of the novelty factor,[26] which aligns with the increase in correct scores in the present study. The total number of patterns produced increased, and the absolute values also revealed the actual number of incorrect answers post-MWT. We believe that an important military skill is the ability to make a few mistakes in stressful situations. Therefore, presenting the absolute numbers of correct and incorrect designs may describe the results as more neutral than relative values.

The most pronounced effects of stress are usually found in more complex tasks. This was manifested in a previous study on applicants to the Swedish counterterror intervention unit. These subjects showed substantial stagnation in overall DF test performance and decrements in the more complex DF 3 during a 10-day physically and psychologically demanding field assessment.[4] These patterns were not seen among the cadets in the present study. One possible explanation is the relatively low workload and stress during the MWT. The Swedish counterterror intervention unit field assessment[4] likely induced more severe physical and psychological pressure than the MWT in the present study. It is reasonable to believe that a more rigorous military exercise would cause a higher stress response, producing a more pronounced decline in cognitive performance. Furthermore, it is worth noticing that the number of incorrect DF 3 scores was unchanged at the post-test and that cadets with lower stress responses made fewer incorrect designs than the more stressed cadets. The ability to conduct high-precision work and avoid mistakes are of great importance for personnel in some military contexts, for example, explosive ordnance disposal or conduct of indirect fire. More rapid and less precise work is favourable in other situations.

The non-linear HRV variable SD1/SD2 was used in the analyses of stress response. The SD1/SD2 ratio is not closely related to HR, and therefore less sensitive to variations in resting HR caused by other factors (eg, dehydration, physical activity, breathing frequency). The SD1/SD2 variable correlates to the relationship between high-frequency and low-frequency variations in HRV (LF/HF ratio).[29] LF/HF ratio has also been shown to be less related to HR but requires more extended recording periods,[29] which was deemed inapplicable in the present study. Also, more consistent responses are seen in the non-linear domain metrics (SD1 and SD2) of HRV compared with frequency domain measures (LF/HF ratio) in response to acute stressors.[20] Different protocols and various analysis methods complicate the interpretation and comparisons of previous studies.

We have developed a new tool for the assessment of individual military performance and leadership skills. The 6-point Likert scale was accompanied by words where 1 represented a performance 'well below normal standards' and 6 represented a performance 'well above normal standards'. Results showed that the officer-assessed military performance was related to the objectively measured physiological stress (HRV); the cadets who displayed less stress also achieved the highest scores for military performance. High stress levels during military training resulted in lower scores, but this was unrelated to VO_2max. Notably, we found these relationships between stress and performance during a standard military training session.

A possible limitation of the present study is the lack of a proper resting HRV measurement. It has been shown that HRV is influenced by anticipatory anxiety,[30] where the cognitive anticipation of the task elicits a physiological stress response before the commencement of the task, lowering baseline HRV. However, this study focused on the capacity to preserve cognitive and military performance regardless of stress and prolonged exercise. Individual performance in the rested state is less important than the capability to remain unaffected and focused during and after a challenging task. Future studies could be done to examine the decline in cognitive function during prolonged military exercises and identify the predictive and mediating factors that influence this decline. This could not be done in the present study due to the small sample size.

Another limitation is the use of officer-assessed military performance as an overall measurement of cadets' behaviour in a military context. Similar ratings of military performance have been done previously by Køber *et al*.[15] The 6-point scale that was used in the present study has not yet been validated against more precise measures (eg, marksmanship, reaction time) and does not capture skills in military tactics and strategy. However, our data indicate that the 6-point scale possesses meaningfully strong concurrent validity to biological stress (ie, HRV) in applied military settings. The use of the scale seems feasible in the intended population (officers), based on the reactions from the military staff during the study.

Finally, the study has limitations due to the low number of female participants. Sex-specific analyses would have contributed to the results, but women are a minority in the Swedish Armed Forces and, thus, more challenging to recruit to research.

Even though the individual military performance is related to stress response and cardiorespiratory fitness, no causality can be proven. Future studies need to investigate the effects of increases in VO_2max and identify possible 'cut-off' values where further improvements no longer correspond to better military performance.

CONCLUSIONS

The findings provide some evidence that military performance is influenced by cardiorespiratory fitness because high-fit individuals exhibit a lower stress response following prolonged military exercise. Aerobic capacity may provide a meaningful effect on the ability to preserve military performance, and the results are relevant to all personnel in high-risk, high-demand duty.

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Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants. The study was approved by the local ethical committee (Regionala etikprövningsnämnden i Stockholm; ref.

no. 2020-01168) and was performed in compliance with the Declaration of Helsinki. Participants were given verbal and written information on the study and gave their informed consent to participate in the study before taking part.

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