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CARDIOVASCULAR, HORMONE, AND LIPID RESPONSES TO STRESS INDUCED BY VIRTUAL CRANE HANDLING

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Abstract
Objectives: The aim of the study was to test whether a mixed-mock-up-simulator (MMU-simulator) is suitable for on-the-job training by measuring stress reactions induced by handling a crane in a virtual environment in subjects not experienced in crane operation. **Materials and Methods:** A MMU-simulator in a virtual environment was developed. Twenty three individuals were randomly divided into Group 1 (n = 13) and Group 2 (n = 10). They had the task of transporting a weight over barriers with a virtual crane twice in two 15-min intervals with a 15-min break in between. Acoustical and optical disturbances were generated as an additional strain for Group 1 in the second interval and for Group 2 in the first interval. Heart rate (HR) and blood pressure (BP) were measured consecutively in both groups, blood sampling was performed in Group 1. Plasma concentrations of stress hormones and lipids were analyzed. Data were calculated as the percentage of baseline values. **Results:** Compared to rest courses, strain led to a significant increase in HR and BP except diastolic BP in Group 2. Apart from an increased systolic BP under additional stress in Group 2, no significant differences were found between the two strain courses. Concentrations of epinephrine showed the highest increase under strain with a mean of 67%. The mean increase in norepinephrine and cortisol was 23% and 7%, respectively, whereas a 4% increase was observed for total cholesterol and high density lipoprotein cholesterol. These differences between "Rest" and "Strain" were significant. After adjusting for total plasma protein concentration, stress hormones, but not lipids, were still significantly higher during strain. **Conclusions:** The elevation in lipids during acute stress could be interpreted as an effect of hemoconcentration due to vasoconstriction by catecholamines. The significant increase in cardiovascular parameters and stress hormones during the tasks demonstrate that working in a virtual environment generates mental strain and that the developed MMU-simulator appears to be a promising device for on-the-job training. However, further research is necessary to validate the usefulness of virtual training by means of a comparative study of virtual and real-world training.

Key words:
Virtual crane handling, Cardiovascular reactivity, Stress hormones, Lipids

INTRODUCTION

Application of virtual environments (VEs) is based on computerized generation, perception and manipulation of naturalistic or abstract three dimensional virtual reality (VR) [1–3]. VR simulations allow to visualize work environments, objects and procedures and to manipulate these

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interactively. By the integration of human-machine-interfaces and their effects on humans, VEs represent versatile and flexible applicable methods for designing workplaces and procedures. For instance, they permit the simulation of hazard and strain situations without exposing a person to a real danger. VR simulations have the potential to create an environment which seems to be actually real [4–5].
Virtual crane handling provides applications for on-the-job training. However, up to now it is not clear how far these applications can be put into practice, and if or where restrictions are to be expected. Therefore, it should be investigated if strain can be generated in a virtual environment close to reality. For this purpose, an experimental design for simulation of transporting and controlling operations in a bridge crane was developed. Several task-oriented performance requirements and environmental-oriented load factors were simulated, and their influences on the test subjects' demand and performance were examined.
To evaluate the amount of stress in this study, psychophysiological reactions of heart rate (HR), blood pressure (BP), and stress hormones epinephrine (E), norepinephrine (NE) and cortisol (CORT) were measured.
It has been reported that individuals who are exposed to acute real psychological stress display significant elevations in total cholesterol (TC) [6–9]. Therefore, TC and high density lipoprotein cholesterol (HDLC) were measured to evaluate the effect of virtual stressors.

MATERIALS AND METHODS

Mixed-mock-up-control stand

The VE used in this study was created in the fully immersive, cubic stereo-projection room HyPi-6 (hybrid personal immersion system featuring 6 walls) [4]. The MMU-control stand in the three-dimensional VE was developed to examine strain and performance parameters by driving a hall bridge crane. The crane could be traversed in three axes. The control of the crane was implemented by means of a crane's common steering-seat which was fixed in the position at the entrance to HyPi-6 (Fig. 1). The right lever grip controlled the movement in the x-y-direction (traversing), and the left lever grip controlled the movement in the z-direction (up-down). The load-magnet could be activated by an additional switch so that the participants could hook on and off by themselves. The haptic setting of this MMU-cockpit enhances the immersion for the participant.
In order to auralize the simulation, sounds from the surroundings of a real bridge crane were recorded and synchronized with the motor movements in the simulation. The sounds were played-back by both two active studio speakers and a subwoofer.

Crane control task

A task was developed on the basis of VDI-guideline 2194 [10] for the professional training of crane drivers. It featured three subtasks of increasing difficulty and in-

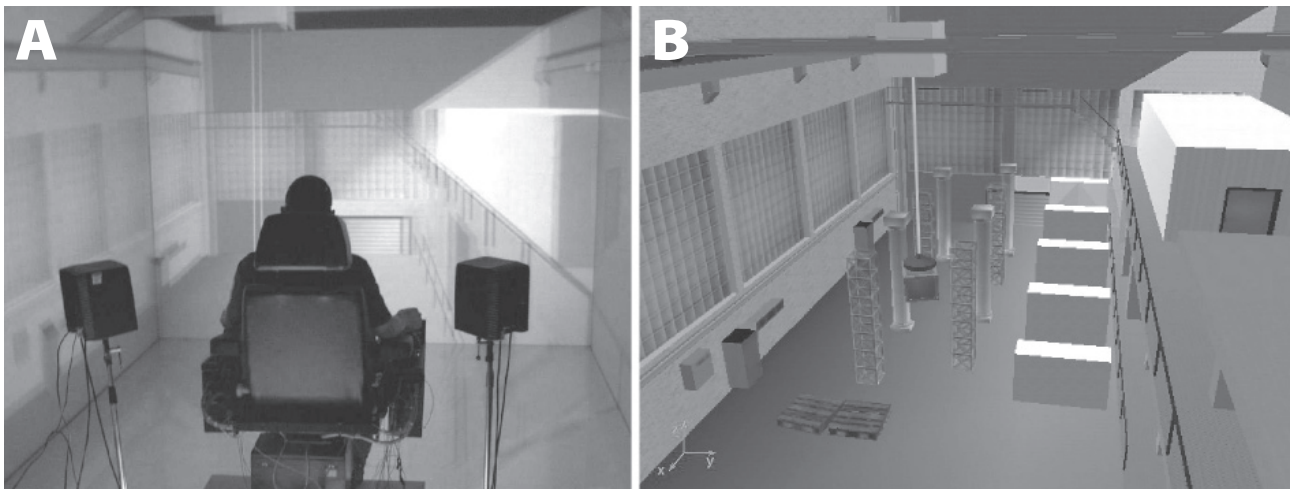

Fig. 1. Setting in the hybrid personal immersion system featuring 6 walls (HyPi-6). A: crane steering seat. B: screenshot of the virtual shop floor.

cluded driving around pillars and 'hopping' over walls. It allowed a continuous performance measurement as well as the application of additional stressors. These stressors were impulses of white noise and irritating radio transmissions as acoustic disturbances, reduction of visibility as optical disturbance, time pressure, and monetary penalties.

Subjects and procedure

Twenty three individuals (20 men, 3 women), aged 20 to 50 years, participated in the study. Primary diseases were excluded by medical history. The subjects were divided randomly into two groups: Group 1 (n = 13) and Group 2 (n = 10).

The procedure started every day at the same time (10:00 a.m.) due to circadian rhythm of psychophysiological parameters with a detailed introduction, a five-minute test crane drive and a medical anamnesis and check-up. During and after introduction and anamnesis, participants were sedentary and had no further mental or physical activity.

At 12 consecutive time points, 10 ml blood samples were taken and HR and BP were measured in Group 1 (Fig. 2). Blood sampling and measurement of HR and BP started 10 min before (-10 min) each participant passed through the first strain course of 15-min duration. After a resting period of 15 min, the participants passed through the course again with the same duration. This time, the additional stressors were applied. In the following rest course, measurements were performed at time points 50 and 75 min.

Group 2 (n = 10) carried out the same procedure but the order of the two strain courses was reversed, i.e. participants first passed the strain course with additional stressors. The aim of this experiment was to check if the order of the experiments caused any differences in psychophysiological reactions. In order to avoid additional stress only the non-invasive cardiovascular parameters HR and BP were chosen for assessing the demand reaction. These parameters were measured according to the time course given in Fig. 2 at 11 time points (the 75-min time point was omitted).

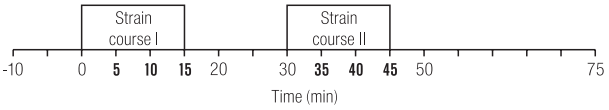

Fig. 2. Study design: measuring of cardiovascular parameters and blood withdrawals in Group 1 at 6 time points in rest (regular numbers) and at 6 time points with strain (bold numbers). In Group 2, only 11 time points existed because the 75-min measurement was omitted. Additional stressors were present in Strain course II for Group 1 and in Strain course I for Group 2.

The performance of the participants was continuously documented while running through the three subtasks to be sure whether they fulfilled the study task.

Determination of heart rate and blood pressure

Heart rate was measured with a puls-chronometer (Vantage Polar, Finland), BP by the method of Riva-Rocci with a semi-automatic device (Space-Labs, Inc., USA).

Plasma parameters

Plasma concentrations of epinephrine, norepinephrine, and cortisol were determined. Additionally, we measured total cholesterol, high density lipoprotein cholesterol and total protein (TP) concentrations in plasma samples.

Blood was drawn into tubes containing ethylenediamine tetraacetic acid (EDTA). The samples were immediately placed on ice and centrifugated at 4°C. Aliquots of each sample were stored at -70°C until assayed for E, NE, CORT, TC, HDLC, and TP concentrations.

Assays

Plasma E and NE were determined by high performance liquid chromatography in one run, using a Merck Hitachi system (Darmstadt, Germany) with an electrochemical detector. Catecholamines were purified, separated by ion-pair reversed-phase liquid chromatography (Recipe, Munich, Germany), and quantified electrochemically. The detection limit for E and NE was 6.0 pmol/L. The intra-assay coefficients of variation of all components were between 7 and 12%. Reference ranges for E and NE in peripheral blood are between 55–437 pmol/L and 590-3550 pmol/L, respectively.

Plasma CORT levels were assayed using a competitive chemiluminescence immunoassay technique (ADVIA

Centaur, Bayer Diagnostics, Fernwald, Germany). The intra-assay coefficients of variation were 3.7% at 107.0 nmol/L, 2.9% at 391.0 nmol/L and 3.0% at 1025.0 nmol/L. The inter-assay coefficients of variation were 5.5%, 3.1% and 4.0%, respectively. The detection limit was 5.5 nmol/L. The reference range at 8.00 a.m. is between 119 and 618 nmol/L. TC was measured by enzymatic color test (Roche Diagnostics, Mannheim, Germany). HDLC was determined by the same method after precipitation of apolipoprotein B containing lipoproteins with phosphotungstic acid and $MgCl_2$. TP was determined by the biuret method.

Ethics

This study was approved by the Ethics Committee at the University of Tübingen.

Data and statistical analysis

Data were calculated as the percentage of baseline values (0-min time point), which were set to 100%. Data are shown as mean ± standard error of the mean (SEM).

For each participant mean value of parameters in Strain course I (5, 10, 15 min) and Strain course II (35, 40, 45 min) were calculated as well as the mean for "Rest" (0, 20, 30, 50, 75 min in Group 1; 0, 20, 30, 50 min in Group 2) and "Strain" (5, 10, 15, 35, 40, 45 min). The values of measured blood chemical parameters were adjusted to total plasma protein concentrations in order to take account of the plasma volume changes during the tasks.

For statistical analyses, the paired t-test was applied. The assumption of a normal distribution was tested using the method of Kolmogorov and Smirnov (GraphPad Instat 3.06). A level of statistical significance was set at a value of $p < 0.05$.

RESULTS

The MMU-simulator induced immersion and resulting presence of all participants in both groups. They finished the given task. However, some participants complained about a bad visual resolution in a given VE.

Table 1. Characteristics of the participants in Group 1 (n = 13) and Group 2 (n = 10) measured at time point 0 min

Prameter	Mean ± SEM	Minimum	Maximum
Group 1			
Age (years)	30.7 ± 2.3	24	50
Heart rate (min^{-1})	75.2 ± 3.8	52	98
Blood pressure systolic (mm Hg)	141.6 ± 4.2	125	173
Blood pressure diastolic (mm Hg)	90.7 ± 3.4	72	114
Epinephrine (nmol/l)	0.38 ± 0.05	0.14	0.64
Norepinephrine (nmol/l)	2.69 ± 0.24	1.45	4.21
Cortisol (µg/l)	12.5 ± 1.6	5.2	22.3
Total cholesterol (mg/dl)	161.1 ± 9.2	111	217
HDL-cholesterol (mg/dl)	41.2 ± 2.4	29	55
Group 2			
Age (years)	25.4 ± 1.1	21	31
Heart rate (min^{-1})	75.9 ± 3.4	65	100
Blood pressure systolic (mm Hg)	126.6 ± 3.3	106	143
Blood pressure diastolic (mm Hg)	82.7 ± 2.8	68	93

SEM – Standard error of the mean.

The values of time point "0 min" of participants in Groups 1 and 2 are shown in Table 1. Whereas HR was comparable between the groups, average systolic BP was 15 mm Hg higher in Group 1. Mean concentrations of E (0.38 nmol/l), NE (2.69 nmol/l), CORT (12.5 µg/l), and TC (161.1 mg/dl) were within reference ranges. Mean concentration of HDLC (41.2 mg/dl) was within reference range for men.

Cardiovascular parameters were increased during both strain courses in Group 1 (Fig. 3A–C). The highest mean increase in a single time point was 17% for HR, 7% for systolic and 11% for diastolic BP. Statistical analyses did not reveal significant differences between Strain course I and Strain course II with supplementary stressors (Table 2).

In Group 2 (Fig. 3D–F), the highest mean increase was 28% for systolic BP at 10 min of Strain course I. The mean increase in HR (6% at 5 min) and diastolic BP (8% at 5 min) was lower. Systolic BP was significantly higher in Strain course I (with supplementary stressors) compared to Strain course II ($p = 0.0025$), but HR and diastolic BP did not show significant differences between the two strain courses (Table 2).

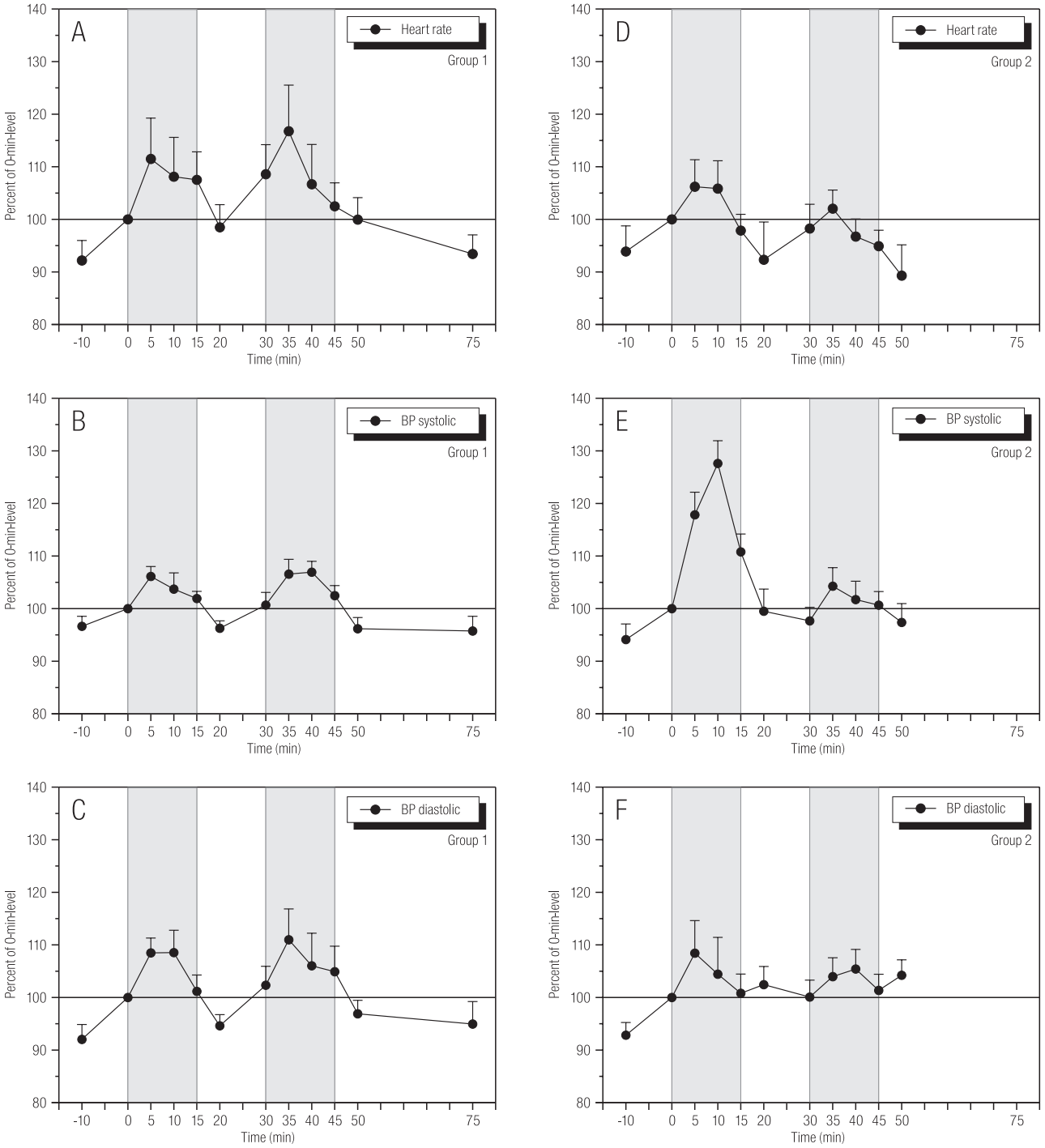

Fig. 3. Time course of heart rate (HR) and blood pressure (BP) relative to basal values at 0 min in Group 1 (n = 13), A–C, and Group 2 (n = 10), D–F, shown as mean ± SEM.

Summarizing all 5 (4 for Group 2) measurements under rest and all 6 measurements under strain for each participant and comparing "Rest" with "Strain", HR and systolic and diastolic BP were significantly different in Group 1. In Group 2, HR and systolic BP showed a significant increase under strain (Table 3).

Concentrations of E showed a stronger increase during strain compared to NE and CORT (Fig. 4). The highest mean concentration of a single time point was 180% for E, 127% for NE and 113% for CORT. Maximum values of some participants (not shown) were above 300% for E, above 200% for N and above 150% for CORT. Compari-

Table 2. The percentage of 0-min level of measured parameters during Strain course I and Strain course II in Group 1 (n = 13) and Group 2 (n = 10) (mean ± SEM of calculated mean values of each participant during the two strain courses)

Parameter (%)	Strain course I	Strain course II	P
Group 1			
Heart rate	107.5 ± 4.8	114.4 ± 4.5	0.3435
Blood pressure systolic	102.5 ± 1.6	104.7 ± 1.5	0.2405
Blood pressure diastolic	104.3 ± 2.7	108.2 ± 3.7	0.2543
Epinephrine	159.4 ± 12.6	173.6 ± 13.4	0.2031
Norepinephrine	119.8 ± 6.6	125.2 ± 9.5	0.3258
Cortisol	108.5 ± 3.7	105.7 ± 7.3	0.6243
Total cholesterol	103.6 ± 1.1	104.5 ± 1.3	0.3172
HDL-Cholesterol	103.4 ± 1.1	103.5 ± 1.1	0.9505
Group 2			
Heart rate	103.3 ± 4.0	98.5 ± 2.8	0.1140
Blood pressure systolic	114.4 ± 3.5	102.2 ± 2.7	0.0025
Blood pressure diastolic	103.0 ± 3.1	103.6 ± 2.9	0.7681

SEM – Standard error of the mean; P – significance level.

Table 3. The percentage of 0-min level of cardiovascular parameters during "Rest" and "Strain" in Group 1 (n = 13) and Group 2 (n = 10) (mean ± SEM of calculated mean values of each participant during rest and strain courses)

Parameter (%)	Rest	Strain	P
Group 1			
Heart rate	100.7 ± 3.1	109.4 ± 4.3	0.0017
Blood pressure systolic	97.8 ± 1.3	103.4 ± 1.3	0.0002
Blood pressure diastolic	97.9 ± 1.8	106.3 ± 2.6	0.0010
Group 2			
Heart rate	95.3 ± 3.4	101.0 ± 3.2	0.0030
Blood pressure systolic	98.5 ± 2.2	107.8 ± 2.8	0.0004
Blood pressure diastolic	101.3 ± 2.0	103.2 ± 2.8	0.3071

SEM – Standard error of the mean; P – significance level.

son between Strain course I and Strain course II (with additional stressors) did not reveal significant differences for E (p = 0.2031), NE (p = 0.3258) and CORT (p = 0.6243) (Table 2). The comparison between "Rest" and "Strain" showed that the increase in E, NE and CORT during strain was significant (Table 4). This did not change after adjustment for TP concentration (Fig. 4; Table 4).

As already seen for stress hormones, the comparison between Strain course I and Strain course II did not show significant differences for lipid parameters (Table 2). Compared to stress hormone concentrations, the increase in TC and HDLC was less pronounced and the highest mean concentration of a single time point was 5% for TC and 6% for HDLC (Fig. 5). But these increases were statistically significant as shown in Table 4. However, after adjustment for TP concentration (Fig. 5), no significant changes in lipid concentrations could be detected under strain (Table 4).

Table 4. The percentage of 0-min level of hormone and lipid parameters during "Rest" and "Strain" in Group 1 (n = 13) before and after adjustment for total plasma protein concentration (mean ± SEM of calculated mean values of each participant during rest and strain courses)

Parameter (%)	Rest	Strain	P
Epinephrine	103.9 ± 6.5	165.9 ± 11.9	< 0.0001
Epinephrine/protein	103.7 ± 6.4	161.9 ± 12.3	< 0.0001
Norepinephrine	111.1 ± 6.2	122.6 ± 7.7	0.0012
Norepinephrine/protein	108.9 ± 5.8	119.2 ± 7.1	0.0009
Cortisol	98.7 ± 3.8	107.1 ± 5.1	0.0015
Cortisol/protein	97.5 ± 3.4	103.9 ± 4.9	0.0156
Total cholesterol	100.1 ± 0.9	104.1 ± 1.1	0.0002
Total cholesterol/protein	99.7 ± 0.3	100.7 ± 0.6	0.1281
HDL-Cholesterol	99.5 ± 0.8	103.5 ± 1.0	0.0004
HDL-Cholesterol/ protein	99.3 ± 0.9	100.7 ± 1.1	0.1042

SEM – Standard error of the mean; P – significance level.

DISCUSSION

Insufficient experience and information, despite being strongly motivated, may have serious consequences in controlling complex engineered conveyors, such as bridge cranes and related mechanical systems with complicated cockpits. Due to an unknown technical fault or defect, the operator may experience a sudden distress, fear or even panic. These can misguide to careless actions sometimes with disastrous consequences. Therefore, applicants for such jobs must get an on-the-job training. However, on-the-job training is expensive and impede a daily routine work. To avoid these circumstances, VR systems offer a possible alternative way for training. These systems must

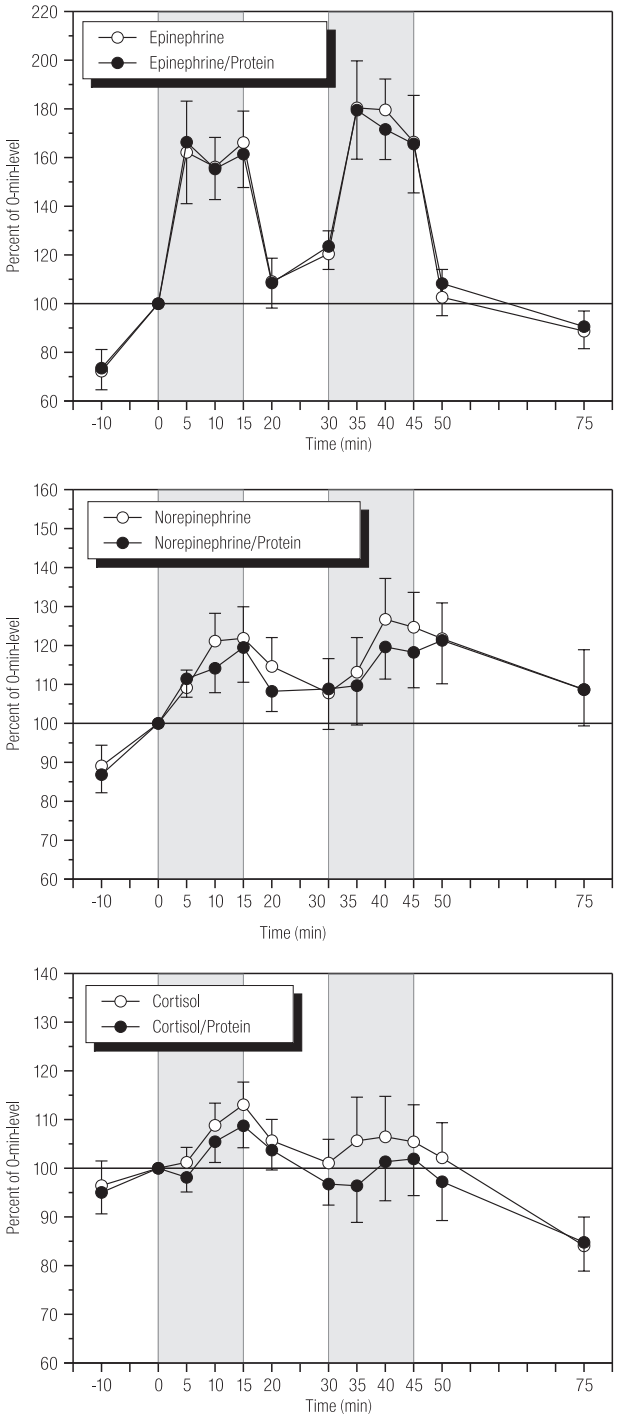

Fig. 4. Time course of stress hormones relative to basal values at 0 min in Group 1 (n = 13) before and after adjustment for total protein concentration (mean ± SEM).

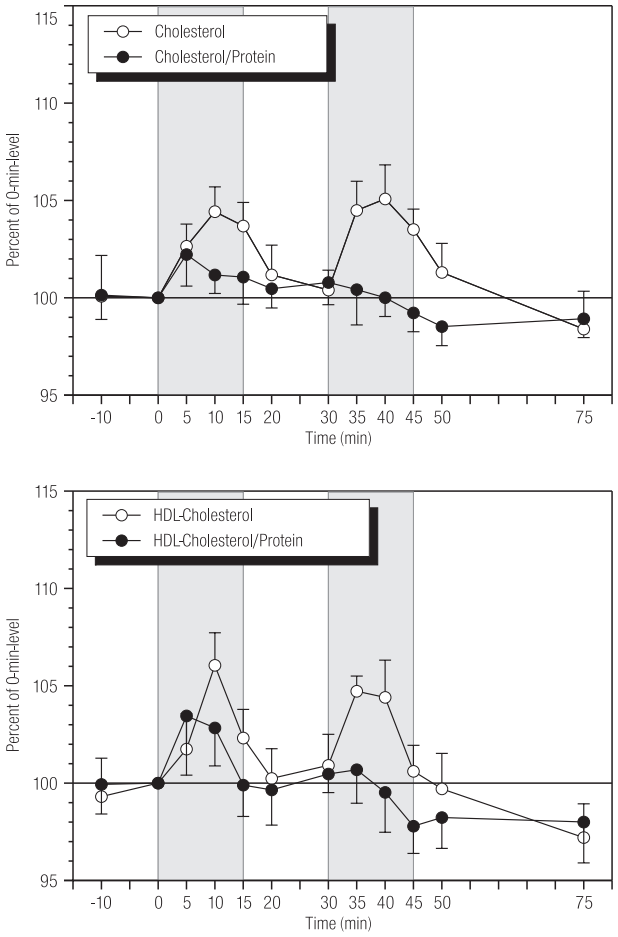

Fig. 5. Time course of cholesterol and HDL-cholesterol relative to basal values at 0 min in Group 1 (n = 13) before and after adjustment for total protein concentration (mean ± SEM).

be validated to check whether they are suitable for implementation. Therefore, we investigated the potentials and the limitations of VR simulations for workplace design by creating simulated work-related stress and strain caused by handling a bridge crane in VEs.

The hall bridge crane simulator was built in a MMU-configuration with full functionality. Thus, immersion and resulting presence of the participants could be induced [3]. Some participants complained about bad visual resolution of depth; this is due to a systematic technical deficiency of VEs that are unable to serve all of the human perception channels. The resulting lack of information or resulting disinformation is known to cause perception problems in VR. Currently, there is no technical solution to that problem [5].

Plasma concentrations of stress hormones, E and NE, increased significantly while the participants were performing the task of transporting a weight with the virtual crane in a VE. The CORT response was less pronounced than that of E and NE.

In the participants, BP increased synchronously to their stress hormone responses during strain. While supple-

mentary stressors, such as strokes of noise and light, did not intensify these effects in Group 1 in the second strain course, they led to a higher systolic BP in the first strain course of Group 2. This could mean that the training effect obtained in the first strain course increased the immersion and presence of participants in Group 1. Fatigue could be excluded because the task intervals lasted only 15 min and all participants performed the tasks with great interest.

Several investigations have demonstrated that individuals exposed to short-term psychological stressors show small but reliable increase in blood lipid concentrations. Studies on individuals engaged in an acute mental arithmetic task [6], a public speaking task [7], a stroop color-word conflict task [8], and a mirror tracing task [9] have all reported reliable increases in TC and LDLC concentrations, relative to baseline concentrations. In this study, we measured concentrations of TC and HDLC to see if this effect also occurred during virtual crane handling. It was found that TC and HDLC concentrations were significantly increased during strain. However, these increases were no longer observed after adjustment for total plasma protein changes. Therefore, the elevation in lipids during acute stress could be interpreted as an effect of hemoconcentration due to vasoconstriction by catecholamines [11].

A significant increase in stress hormones and cardiovascular parameters show that the MMU-simulator developed for crane handling in a VE is a suitable system for stress generation. Strong psychic reactions could not be induced in the VE if there were no real consequences of the user's actions. However, this trait may include new and effective opportunities for professional instruction and training aimed at danger prevention. Hence, future research projects have to investigate the potential of such simulation techniques for training of workers with respect to special needs and dangers of a particular production system. Professional training of crane drivers as well as their training for developing skills to cope with dangerous situations, such as oscillation of the crane load may serve as an example. This seems to be the best way to increase efficiency and reduce costs as well as to decrease the number of accidents.

CONCLUSIONS

It was shown that the MMU-simulator developed for VR tasks in VE generates psychophysiological demand reactions as evidenced by significant elevations of E, NE and CORT concentrations and cardiovascular parameters (systolic and diastolic BP, HR) during strain. Cumulative stressors, such as strokes of light and noise could intensify the stress reaction, when exposure occurred before accustoming of participants to training and their total immersion in the VE. The elevation in lipid concentrations during acute stress in the task courses could be interpreted as an effect of hemoconcentration due to vasoconstriction by catecholamines. In summary, the MMU-simulator appears to be a promising device for on-the-job training. However, further research is necessary to validate the usefulness of virtual training by means of a comparative study of virtual and real-world training.

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