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Mental task and exercise often occur together. Physiological responses to each of these stressors have been studied independently, yet the interactive effects of these stressors are unknown. Hypothesis: Combined mental and physical stress will produce a synergistic interaction. Methods: Twelve healthy subjects were studied by measuring cardiovascular responses to five minutes of static left handgrip alone (25-35% of maximal handgrip strength), mental arithmetic alone, and combined stimuli in random order. Sympathetic nerve activity (SNA, microneurography), mean arterial blood pressure (MAP, Finapres), heart rate (HR, ECG), and vascular resistance (Doppler) were measured. Results: Physical and combined stressors significantly changed SNA, MAP, HR, and FVR. SNA responses to handgrip and the combined stimuli exceeded responses to mental arithmetic alone ($p<0.05$), yet no significant difference existed between responses to handgrip alone and the combined stimuli ($p=0.33$). The three stimuli increased heart rate similarly ($p<0.0006$). Conclusion: The data refuted the hypothesis: mental task did not synergistically interact or even add to the stress response elicited by handgrip exercise. Thus, these data suggest that mental task and static exercise interact in a redundant manner.

INTERACTIVE EFFECTS OF MENTAL AND PHYSICAL STRESS ON

CARDIOVASCULAR CONTROL

Erin Carpenter Westerholm, B.S.

APPROVED:

Major Professor

Committee Member

Committee Member

Chair, Department of Integrative Physiology

Dean, Graduate School of Biomedical Sciences

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THESIS

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By

Erin Carpenter Westerholm, B.S.

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I would like to thank Dr. Michael Smith, my major professor, for his guidance throughout this project. I also would like to thank all of the subjects that participated in the study, my graduate colleagues, and Dr. Donald Watenpaugh who assisted in the completion of this investigation. Furthermore, I especially want to thank Steve and Wendy Wasmund who not only assisted in the data collection and analysis but were also a great source of encouragement. Most importantly, I would like to thank my family who has served as a great source of support on which I can always depend, particularly my mother and father who instilled in me the motivation and desire to achieve the goals I set in life. They have also provided emotional support and assisted in the editing process. Finally, I would like to thank my husband Erick who has unselfishly given his encouragement to overcome obstacles in order to fulfil this goal. The completed project has resulted in the following paper submitted for presentation and publication:

Westerholm, E.C., S.L.Wasmund, W.L. Wasmund, D.Watenpaugh, and M.L. Smith. Interactive effects of mental and physical stress on cardiovascular control. Presented at Texas Chapter of the American College of Sports Medicine meeting, February, 1998.

Westerholm, E.C., S.L.Wasmund, W.L. Wasmund, D.Watenpaugh, and M.L. Smith. Interactive effects of mental and physical stress on cardiovascular control. Submitted for presentation at the American Heart Association meeting, November, 1998.

Westerholm, E.C., S.L.Wasmund, S.L. Wasmund, D.Watenpaugh, and M.L. Smith. Interactive effects of mental and physical stress on cardiovascular control. Journal of Applied Physiology, in preparation.

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LIST OF ABBREVIATIONS

ACTH	adrenocorticotrophic hormone
ADP	adenosine diphosphate
ANOVA	analysis of variance
bpm	beats per minute
CO_2	carbon dioxide
CRH	corticotrophin-releasing hormone
ECG	electrocardiogram
FVR	forearm vascular resistance
HR	heart rate
Kg	kilogram
LBNP	lower body negative pressure
MAP	mean arterial pressure
mmHG	millimeters of mercury
NASA	National Aeronautic and Space Administration
NO	nitric oxide
O_2	oxygen
Pi	phosphate
POMS	Profile of Mood States
SNA	sympathetic nerve activity

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CHAPTER I

INTRODUCTION

Mental stress evokes physiologic responses that are difficult to determine due to the influence of various factors such as age, sex, race, diet, fitness, and family history (15,16). Despite these factors, the physiologic response to mental stress is elicited through the autonomic nervous system and endocrine function. Stressful mental stimuli often elicit a disturbance of homeostasis that results in a response termed by Cannon as "flight or fight " (6,7). For example, when zebra notice a lion in the wild, a "reflex " evoked by the mental stimulus elicit certain physiologic responses. The characteristics of this response are increased blood pressure, heart rate, cardiac output, and skeletal muscle blood flow, with a decrease in renal and splanchnic blood flow (13).

The purpose of these responses is to restrict blood flow to nonessential capillary beds and redirect the blood to systems of the body required to respond to the stressful stimulus such as the heart and skeletal muscle. The increase in blood flow increases oxygen delivery to and metabolite removal from activated skeletal muscles. Major hormonal changes are also seen during the stress response. An increase in epinephrine acts to reinforce sympathetic activity and the activation of the cortisol system via corticotrophin-releasing hormone (CRH) and adrenocorticotrophic hormone (ACTH) system aids in mobilizing energy stores. The action of the renin-angiotensin-aldosterone system and vasopressin both contribute to the increase and maintenance of blood pressure (15,35). All of these reactions resulting from positive stimuli enable an animal to be more alert and to have the capacity to react physically if required.

Mental stress can be divided into three classifications: cognitive function (hand-eye coordination), emotional stress (test anxiety), and mental task (arithmetic). These stimuli elicit a response historically referred to as the defense arousal pattern (13). This response, like fight or flight, results in increased blood pressure, heart rate, cardiac output, and skeletal muscle blood flow, while a decrease in renal and splanchnic blood flow and forearm skin temperature are seen (13,33).

Cannon studied the physiological responses of animals to a threatening environment. He discovered a hormonal agent "sympathin," that is today known as norepinephrine and epinephrine. From the observed responses he developed the idea of "flight or fight" (6,7). Selye studied the responses of animals to persistent painful stimuli; he observed an enlarged adrenal cortex and a substantial increase in the hormone blood levels of epinephrine and norepinephrine (31). He termed this response a stress syndrome and hypothesized that the response pattern was nonspecific to a wide variety of stimuli (31). Further research has supported this hypothesis demonstrating little variation in the physiological response, except in experiments involving subjects with chronic disease (19).

Brod *et al.* performed some of the first studies dealing with mental stress in humans (5). In his studies subjects were required to perform mental arithmetic exercises, while being encouraged to increase the accuracy of their answers and the rate at which answers were given. The response pattern seen was similar to the response described in the defense arousal pattern. Although blood pressure increased in all subjects; the cardiac output response varied. The only subjects that showed a consistent increase in peripheral vascular resistance and reduction in cardiac output were subjects with hypertension. In all of the subjects, renal vascular resistance increased, while forearm vascular resistance decreased during the mental arithmetic tests (5,25). This indicates that skeletal muscle vasodilation could be a response to mental arithmetic and, thus, is consistent with the data and hypothesis originally presented by Cannon (6,7).

In another mental stress study, Hjemelah *et al.*, used the Stroop color test as a stimulus (13). The Stroop test involves naming the color of a word printed in a different color. For example, stress is induced when the word blue is printed in red. Hjemelah *et al.* observed a physiological response pattern similar to the defense arousal pattern. This form of mental stress resulted in an increase in blood pressure (73%), a decrease in systemic vascular resistance (30%), and an increase in heart rate (47%). He also recorded the association of neuroendocrine and cardiovascular responses to mental stress. For example, blood epinephrine levels in the arteries increased greater than 100% above baseline measurements, yet peripheral venous epinephrine levels were lower due to tissue extraction (13). These data are similar to those described earlier by Cannon and Selye and therefore suggest that various mental "stressors" or tasks evoke consistent physiological responses.

The above research has shown that physical and mental stresses are positive stimuli that elicit similar physiological responses. When these stimuli are provoked simultaneously, the physiologic response commonly observed is due to a reflex mechanism of the mental stress stimulus. For example, when a wild animal notices a predator the mental stress stimulates physiologic responses. This response is mediated by the autonomic nervous system through a decreased firing rate of baroreceptors. Both stimuli have been evaluated separately; however, the mechanism of interaction has not been considered extensively. Research of these excitatory stimuli logically led to the study of the interactive effects of multiple stresses.

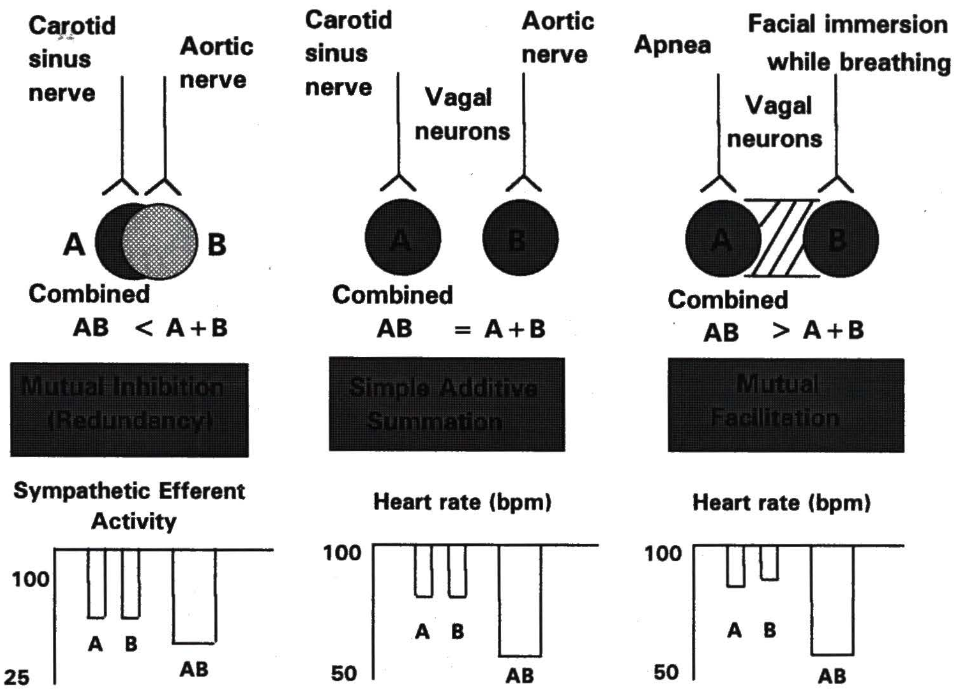
Studies have been done dealing with the interaction of similar stimuli. These interactions involved comparing two sensory inputs activated simultaneously, each having the same influence (inhibitory or excitatory) on the autonomic nervous system. Three general types of interaction were observed: mutual inhibition, simple additive, and mutual facilitation (2).

Mutual inhibition occurs when the combined stimulation yields a response significantly less than the sum of the individual responses. This effect has been demonstrated by arterial baroreflex control of efferent sympathetic nerve activity (Figure I). Kezdi and Geller reported an inhibitory effect when stimulating both the carotid sinus and aortic arch baroreceptors simultaneously in an open-loop system. This was demonstrated when the net effect of the open-loop system was observed to be less than the sum of the individual responses seen in a closed-loop system (2).

Simple additive summation occurs when the combined stimuli are equal to the sum of the individual stimuli. This interaction contrasts the pattern of physiologic changes observed in sympathetic vascular responses. For example, reflex bradycardia can be mediated through arterial baroreflexes (Figure II). The baroreceptors located in the carotid sinus and aortic arch are both innervated by vagal afferent fibers (parasympathetic system). When hypotension or hypertension stimulates vagal neurons in a closed-loop system, both baroreceptors elicit a similar response. Under similar circumstances in an open-loop system these stimuli demonstrated an additive effect that suggests little or no redundancy in the control of vagal outflow to the heart (2).

Mutual facilitation (synergism) occurs when the response to the combined stimulation is greater than the sum of the individual responses. Heistad and Wheeler (Figure III) observed this interaction in an experiment. This experiment involved the stimulus of facial immersion while breathing through a snorkel, which produced a reduction of heart rate. The other stimulus used was apnea or breath holding, which caused a very small reduction in heart rate. The interaction of these stimuli produced marked bradycardia (2). Therefore, the net response of the combined stimuli was greater that the sum of the individual responses.

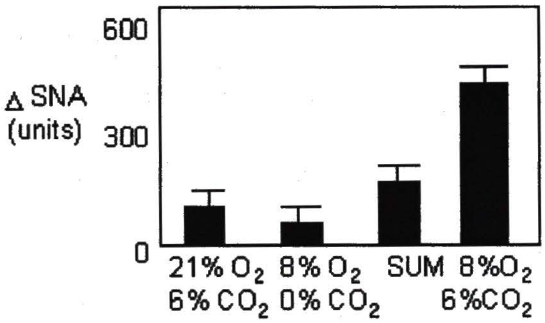
Figure I. Figure II. Figure III.



*Adapted from Abboud *et al.* Handbook of Physiology (1983)

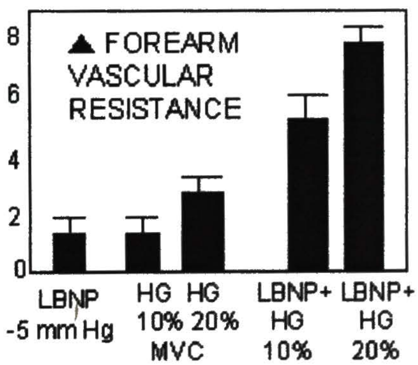
Further research dealing with two excitatory stimuli has shown a synergistic interaction (1,17,32). In a study done by Smith *et al.*, sympathetic nerve activity (SNA) responses to simultaneous stimulation of the O_2- and CO_2-sensitive chemoreflexes are shown in Figure IV. The individual stimuli of hypercapnia and hypoxia were observed and measured followed by the measurement of interactive stimuli. There was an obvious synergistic interaction observed in this study (32). The figure illustrates the response seen in SNA for hypoxia and hypercapnia, however, when the two stimuli are combined a synergism occurs. A study done by Abboud *et al.* examined the influence of a change in baroreceptor activity on the gain of somatic reflex (Figure V). This study used lower body negative pressure and a percentage of the subject's maximal handgrip as the excitatory stimuli. The interaction of these stimuli was also shown to be synergistic. Figure 2b illustrates that the effects of lower body negative pressure (LBNP) and isometric exercise produce a mutually facilitated response (1).

Figure IV.



*Adapted from Smith *et al.*, J Physiol (inpress)

Figure V.



Adapted from Abboud *et al.* Circ Res (1981)

Statement of the Problem

The problem of this study was to determine the interaction that occurs between mental and physical stimuli, by comparing autonomic nervous system activity in the combined and individual stimuli.

Purpose of the Study

The purpose of this study was to quantify the physiological responses of the autonomic nervous system during the interaction of mental and physical stress. The protocol also determined the type of interaction that occurs during the combination of these stimuli compared to the individual stresses. The measure of sympathetic nerve activity and cardiovascular responses in human subjects indicated the interaction between the individual stresses.

Hypothesis

The combined imposition of mental and physical stress will elicit a synergistic response of sympathetic nerve activity, heart rate, and arterial pressure.

NASA Relevance

This research was supported by a research grant from the National Aeronautic and Space Administration (NASA). Therefore, I am compelled to offer a brief discussion of the relevance of this research to NASA. With the construction of the space station about to begin, astronauts face many challenges in space. Astronauts will be building the space station while tethered to an apparatus preventing most motion except for handgrip exercise. The astronauts will perform this forearm exercise while receiving cognitive input about the task they are doing and the environmental conditions around them. This situation probably elicits emotional stress combined with the ongoing mental and physical task. Therefore, this experimental protocol will benefit NASA by aiding in understanding the physiological responses of astronauts under these unique physiological conditions.

CHAPTER II

METHODS AND PROCEDURES

Subjects

The limitations of the subjects and protocol attempted to reduce the number of uncontrolled variables to insure the data are accurate and reliable, so meaningful conclusions could be drawn. The studies in this proposal were approved by the University of North Texas Health Science Center Institutional Review Board. Informed consent was obtained from all subjects.

Twelve healthy subjects between the ages of 20 and 50 years were recruited for this study. Subjects were not discriminated against according to gender or race. They were required to receive a satisfactory score on the Profile of Mood States (POMS) exam. Following recruitment, a session was conducted with each subject prior to the experiment to determine the subject's maximal handgrip strength and to familiarize the subject with the protocol of the experiment. This session also allowed the investigators to become familiar with the subject and any special needs that the subject had.

The test trials were conducted in a random order to avoid a learning curve in the subject's response to the protocol. Fifteen minutes were required between each protocol to allow sufficient time for the subject to return to baseline after each exercise. A maximum of an hour was allowed to acquire a sympathetic nerve signal prior to starting the study.

All subjects were required to participate in the familiarization study and experiment during the approximate same time (morning, afternoon, evening) of day. Females were in the luteal stage of their menstrual cycle to avoid hormonal fluctuations that might affect the validity of the data (14). The record of her last menses and the normal length of her cycle determined the appropriate test days for each female subject's menstrual cycle. Room temperature was held at approximately 22° C throughout the protocol, and all subjects used their left (non-dominant) hand for the static handgrip exercise. These measures were taken to provide consistent environmental and physiological conditions for every subject.

Measurements

Heart rate, arterial blood pressure, sympathetic nerve activity (SNA), forearm blood flow, and calculated forearm vascular resistance were measured. Baseline conditions were established before collecting baseline measurements. Special care was taken to insure that the laboratory was quiet and that the subject was comfortable. Heart rate was obtained from an electrocardiogram and cardiotachometer. Arterial blood pressure was measured non-invasively, by use of a Finapres photoplethysmographic monitor placed around the middle finger (Ohmeda, Inc.). The Finapres instrument was adjusted to match diastolic arterial pressures determined by conventional auscultation.

Muscle Sympathetic Nerve Activity (SNA) was measured in the peroneal nerve (located on the posterior and lateral aspect of the leg near the fibular head) by standard microneurographic techniques. First, the course of the nerve was determined by stimulation through the skin with a pencil shaped electrode. When the nerve was stimulated, involuntary twitching of the calf or foot and/or tingling sensations occurred. The twitching or sensations disappeared when the stimulation ceased. Once the nerve was localized, two tiny, sterile, wire electrodes were inserted through the skin. This was done without local anesthesia since the electrodes were small and did not produce appreciable pain when inserted (tip of diameter approximately 5-10 μm). One electrode was connected to the stimulator and weak electrical shocks were given through the electrode. The position of the electrode was adjusted to elicit muscle twitches without tingling sensations, which indicate a sympathetic nerve signal. Characteristics of muscle SNA include pulse-synchronous bursts of activity occurring 1.2-1.4 seconds after a QRS complex, reproducible activation during phase II and III of the Valsalva maneuver and no response to pinch, skin stroking, or startle that elicit skin sympathetic activation. SNA was normalized within subjects to allow comparisons within and between subjects.

Forearm blood flow was measured with a quantitative Doppler ultrasound of the brachial artery. Forearm vascular resistance (FVR) was calculated as mean arterial pressure divided by forearm blood flow. FVR provided an independent and functional index of SNA.

EXPERIMENTAL DESIGN

Experimental Preparation

The subject was prepared by placing him/her in the supine position on a hospital bed and placing boards under each arm to facilitate physiological measurements. Electrodes were placed on the chest and abdomen for measurement of the electrocardiogram (ECG). A Finapres cuff was placed on the subject 's right hand in order to measure heart rate and blood pressure. A manual blood pressure measurement was taken to compare diastolic pressure with the Finapres signal in order to insure an accurate measurement. When a sympathetic nerve was isolated, its activity was recorded on a computer. All measurements were recorded while an ultrasound of the forearm vessel was found. Once the blood flow measurement was obtained the first randomly selected experiment was begun. Fifteen minutes were required between experiments to permit the subject to return to baseline.

Handgrip Only

Two minutes of baseline data was recorded. The subject was informed to begin gripping at the appropriate percentage of their maximal handgrip (≅ 30%) for five minutes. At this time, a note was made on the computer indicating that the experiment had begun. One of the researchers verbally coached the subject to maintain the handgrip levels at ± 1Kg of their target level. The subject received a 5-second break half way through the 5-minute grip period. When the experiment was completed a minute of recovery was recorded without handgrip.

Mental Only

Two minutes of baseline was recorded at the beginning of the experiment. When baseline was completed, a note was made on the computer indicating that the experiment had begun. At that time, a metronome set at 30 beats/minute was begun while challenging subtraction tasks were given to the subject. The subject was given a 2-digit integer to subtract from a 4-digit integer multiple times. Once the subject had answered five problems or answered incorrectly, the subject was given new numbers. Every time the subject was "buzzed" a note was made on the computer. At the conclusion of the 5-minute experiment, a minute of recovery was collected.

Mental and Physical Combination

Baseline data was recorded for two minutes. The subject was informed to begin gripping at the appropriate percentage of their maximal handgrip ($\cong$ 30%) for five minutes. A note was made on the computer when the experiment had begun. One of the researchers verbally coached the subject to maintain their handgrip level at $\pm$ 1Kg of their target, done exactly the same as the handgrip-only trial. Once the subject stabilizes his/her handgrip, another researcher began the mental task described above. The subject received a 5-second break from the handgrip exercise half way through the experiment. When the experiment was completed, a minute of recovery data was collected.

Statistical Analysis

The design of this study required a 3 x 7 two-factor ANOVA format with repeated measures taken at time intervals. Every subject performed the three experimental stimuli and the measured variables were taken over the following periods of time: baseline, minute one, minute two, minute three, minute four, minute five, and recovery. The design of this experiment permitted comparison of changes in cardiovascular responses and sympathetic nerve activity between each of the stimuli on a minute to minute basis. Measurements of MAP, HR, FVR, and SNA were monitored continuously throughout the entire protocol. The average response for each minute was compared using paired t-test in order to determine when significance was gained and the interaction occurring between the three stimuli. Data are presented as the change in mean response for each stimulus plus or minus and standard error of the mean (SEM). Dependent variables were accepted as significant with an α level of 0.05.

CHAPTER III

RESULTS

Chapter III conveys the findings of this investigation. The data collected is presented below as mean values of the subjects studied for each of the three stimuli. The standard error of the mean is also presented for each mean value obtained. Comparisons were made between the three different stressors in order to determine if independent or interactive effects occurred. The reduction and analysis of the data obtained concentrated on differentiating between the cardiovascular and sympathetic nerve responses to each stimulus.

A comparison of mean arterial pressure (MAP) values indicated no significant difference between trial baselines of the three stressors (see Table I). The physical and combined stressors significantly increased sympathetic nerve activity (SNA), MAP, heart rate (HR), and significantly decrease forearm vascular resistance (FVR). These values and the standard error are found in the table below. SNA responses to handgrip and the combined stimuli for each exceeded responses generated by mental arithmetic stimulus alone ($p<0.05$), yet no significant difference was found between responses to handgrip alone and the combined stimuli ($p>0.05$). The three stimuli increased heart rate similarly ($p<0.0006$).

TABLE I. STIMULI EFFECT ON MEASURED VARIABLES

PEAK Δ	HANDGRIP (PHYSICAL)	MATH (MENTAL)	COMBINED (PHYSICAL + MENTAL)
SNA (burst/min)	12 ± 3 *	2 ± 1	10 ± 3 *
MAP (mmHg)	26 ± 4 *	8 ± 2	23 ± 3 *
FVR (units)	31 ± 10 *	5 ± 4	23 ± 7 *
HR (beats/min)	15 ± 2 *	10 ± 2 *	13 ± 2 *

SNA n = 8; MAP and HR n = 12. No significant difference between trial baselines (p>0.5). *p<0.05 vs. baseline.

The data in Figure VI illustrate the changes in MAP for each stimulus throughout the duration of the experiment. There were significant changes from baseline after the fourth minute of combined stimuli conditions (p<0.05). The recovery responses (off responses) were assessed by paired t-tests that compared the fifth minute of each stimulus to the end of one minute of recovery. The decrease in MAP during recovery was significant for all three conditions (p<0.029), but was not different between the conditions (p>0.18). The data in Figure VII demonstrate that there was no significant difference in the peak effects caused by physical stimulus alone and the combination of physical and mental stimuli (p=0.19). There was also no significant difference between physical and mental stimuli and between mental and the combined mental and physical stimuli (p>0.11).

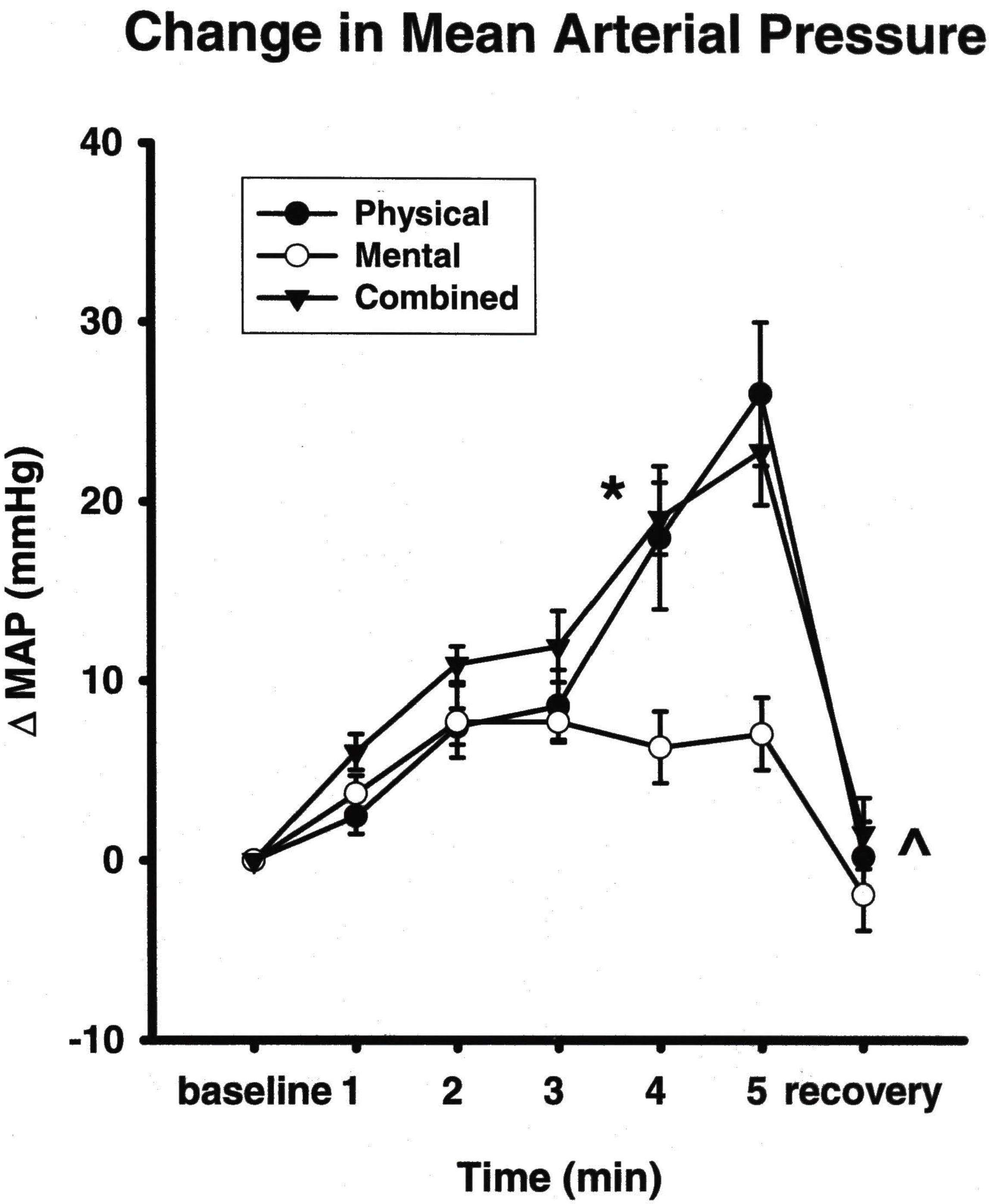


Figure VI. - Average (SEM) mean arterial pressure (MAP) obtained from the three stress stimuli. *p <0.05 vs. baseline
^p <0.05 vs. minute 5

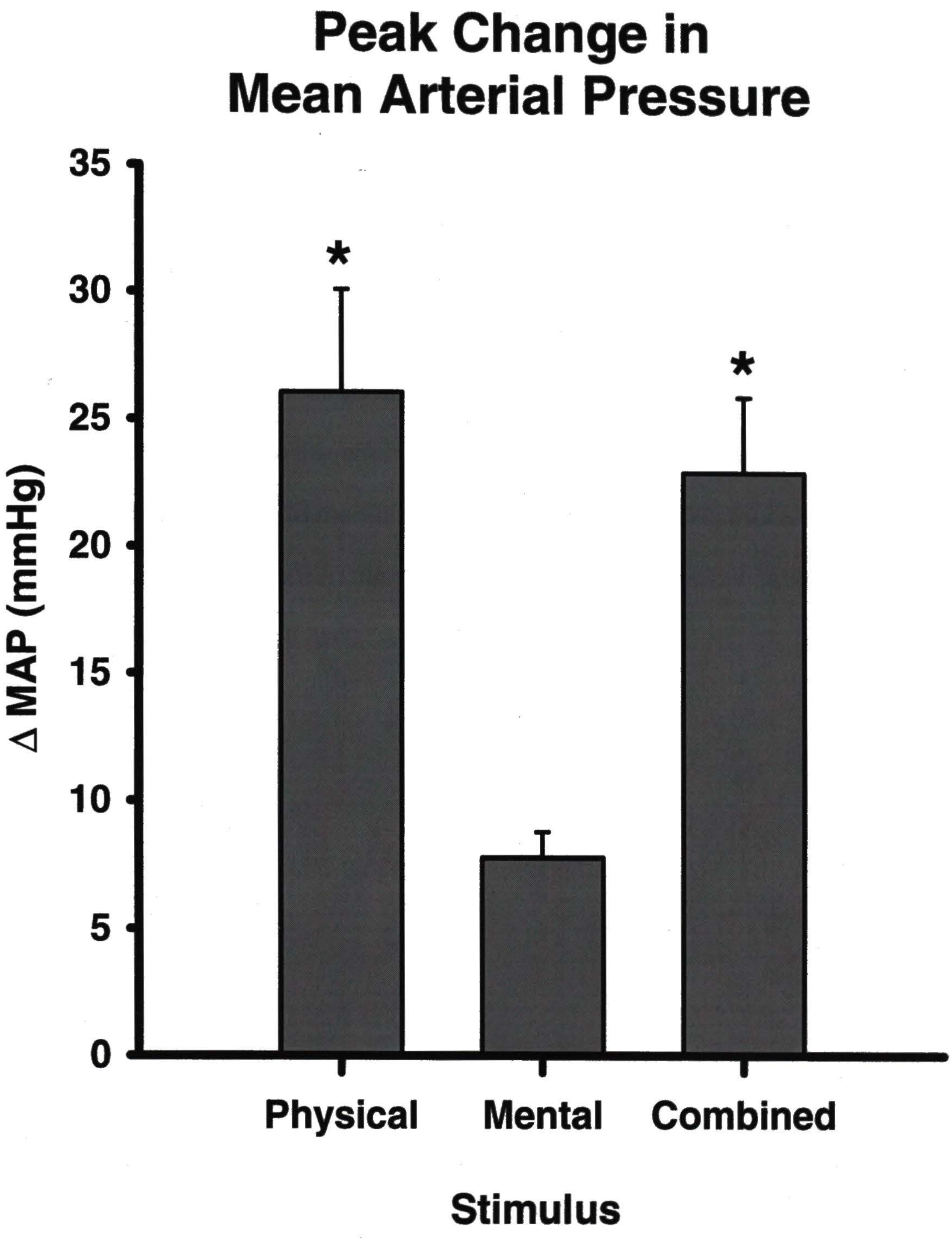


Figure VII. - The mean peak (±SEM) mean arterial pressure (MAP) measurement for the three stress stimuli. **p* <0.05 vs. baseline

The data in Figure VIII illustrate the changes in SNA for each stimulus throughout the duration of the experiment. There were significant changes from baseline after the third minute of static handgrip ($p<0.05$) and the fourth minute of the combined stimuli portion of the experiment exercise ($p<0.04$). Significant off response was detected by paired t-tests that compared the fifth minute of each stimulus to the end of recovery. SNA had significant off responses for the physical and combined stimuli ($p<0.018$). Figure IX demonstrates that there was no significant difference in the effects caused by physical stimulus alone and the combination of physical and mental stimuli ($p=0.33$). However, there were significant differences between mental stimuli and either physical or combined mental and physical stimuli ($p<0.034$).

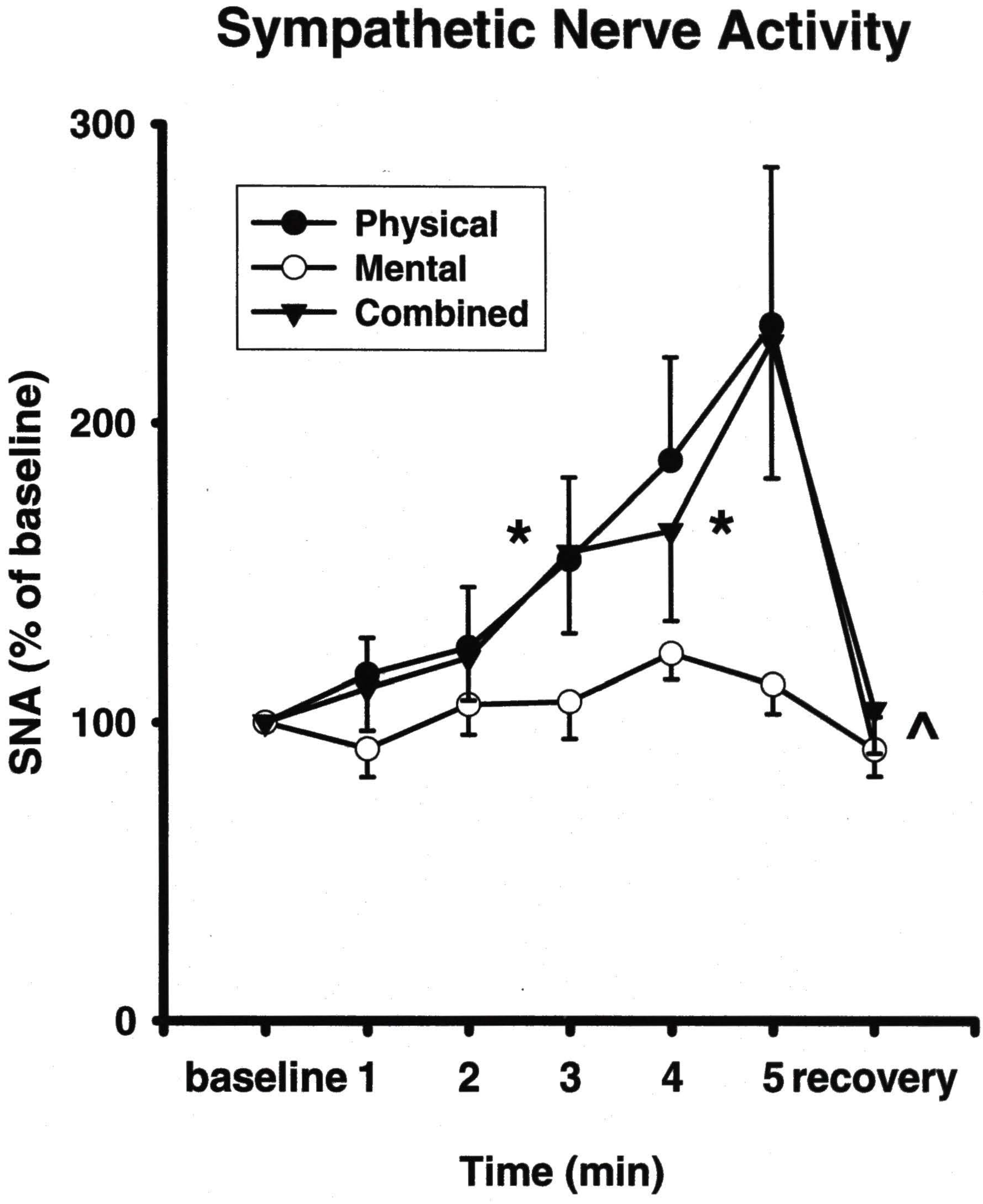


Figure VIII. - The percent change (± SEM) of sympathetic nerve activity (SNA) from baseline. *p <0.05 vs. baseline ^p <0.05 vs. minute 5

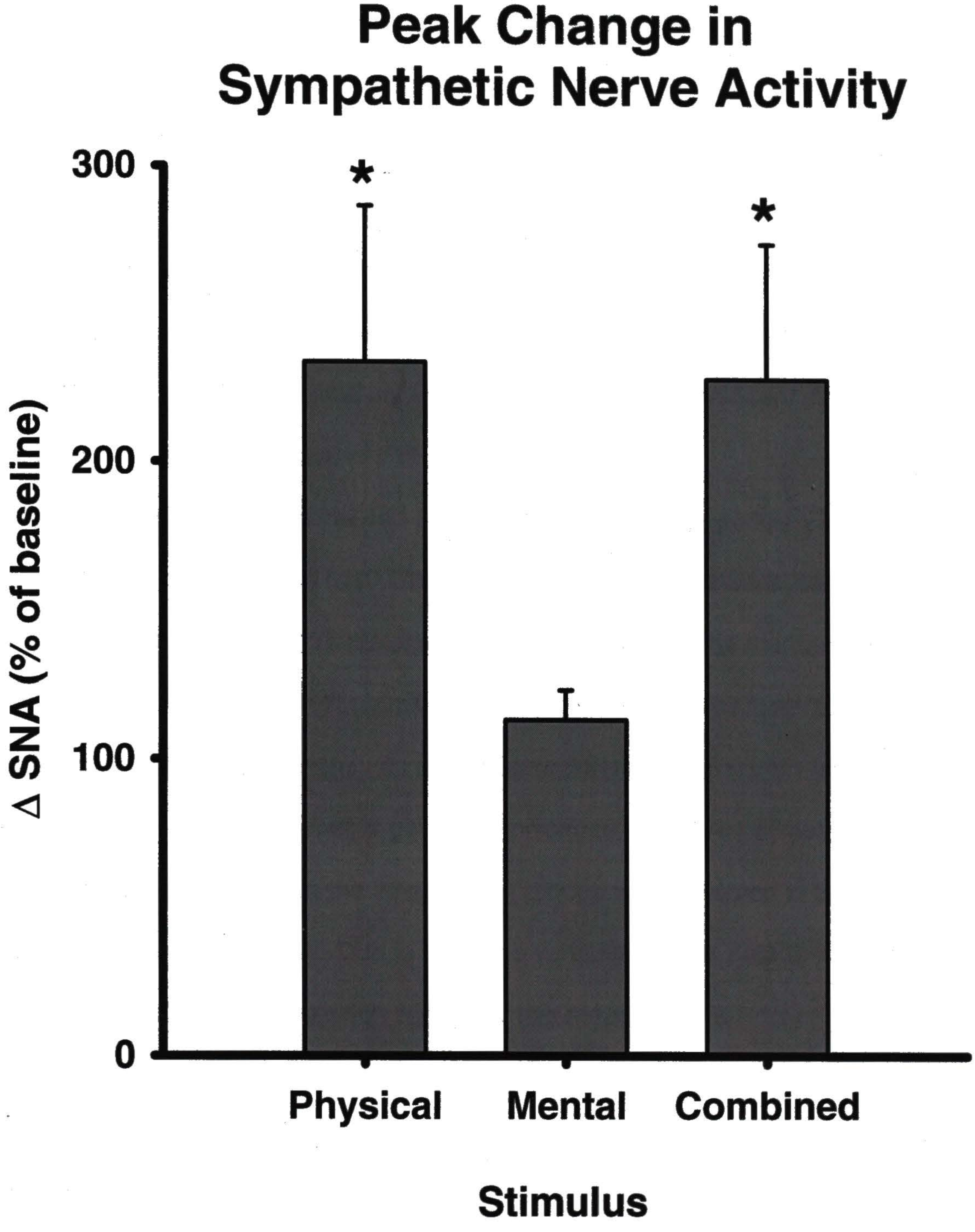


Figure IX. - The percent change (±SEM) in sympathetic nerve activity (SNA) measurement for the three stimuli. *p <0.05 vs. baseline

Changes in forearm vascular resistance (FVR) are represented in Figure X. There were significant changes from baseline after the fourth minute of static handgrip and combined stimuli ($p<0.05$). Figure XI demonstrates that there was no significant difference in the effects caused by peak responses to physical stimulus alone and the combination of physical and mental stimuli ($p=0.2$). There was also no difference in the peak responses of physical and combined stimuli compared to the mental stimulus. However, there was a significant difference observed in the off response of FVR (Figure XII).

The FVR values decreased the most for the recovery period (1-minute) following physical exercise ($p=0.003$). The combined values were less than the physical ($p=0.01$), but both were significantly different from the mental stimuli alone ($p<0.005$). When FVR recovery values for physical stimuli were compared to the combined values, there was a significant difference ($p=0.018$) for FVR (Figure XII). HR measurements gained significance in all three stimuli, however, the least variation between the three stimuli groups was observed in this measurement (Figure XIII). Due to the large variability of the data there was no comparable differences between stimuli for this measurement.

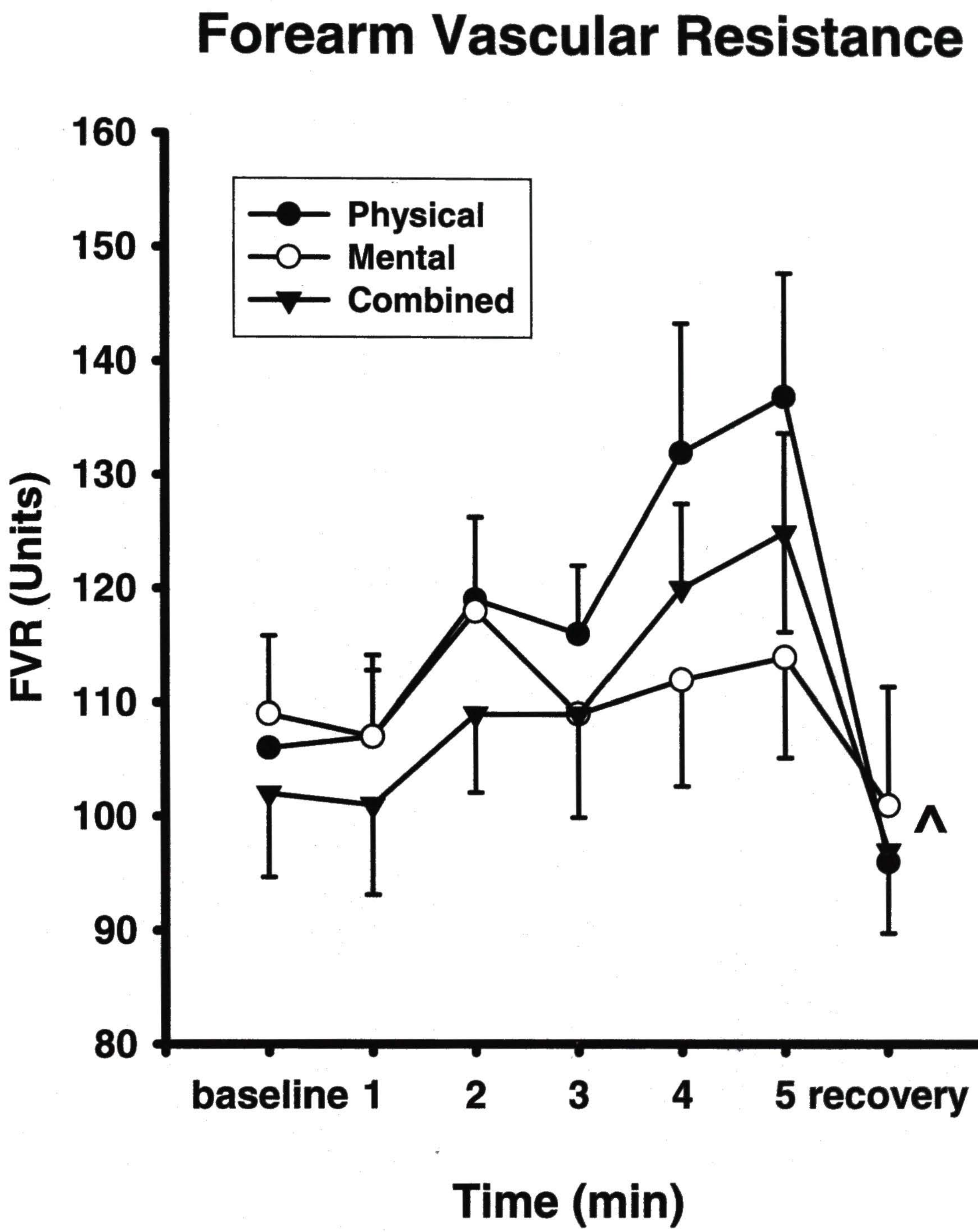


Figure X. - Mean (± SEM) forearm vascular resistance (FVR) data obtained from the three stress stimuli. ^ $p < 0.05$ vs. minute 5

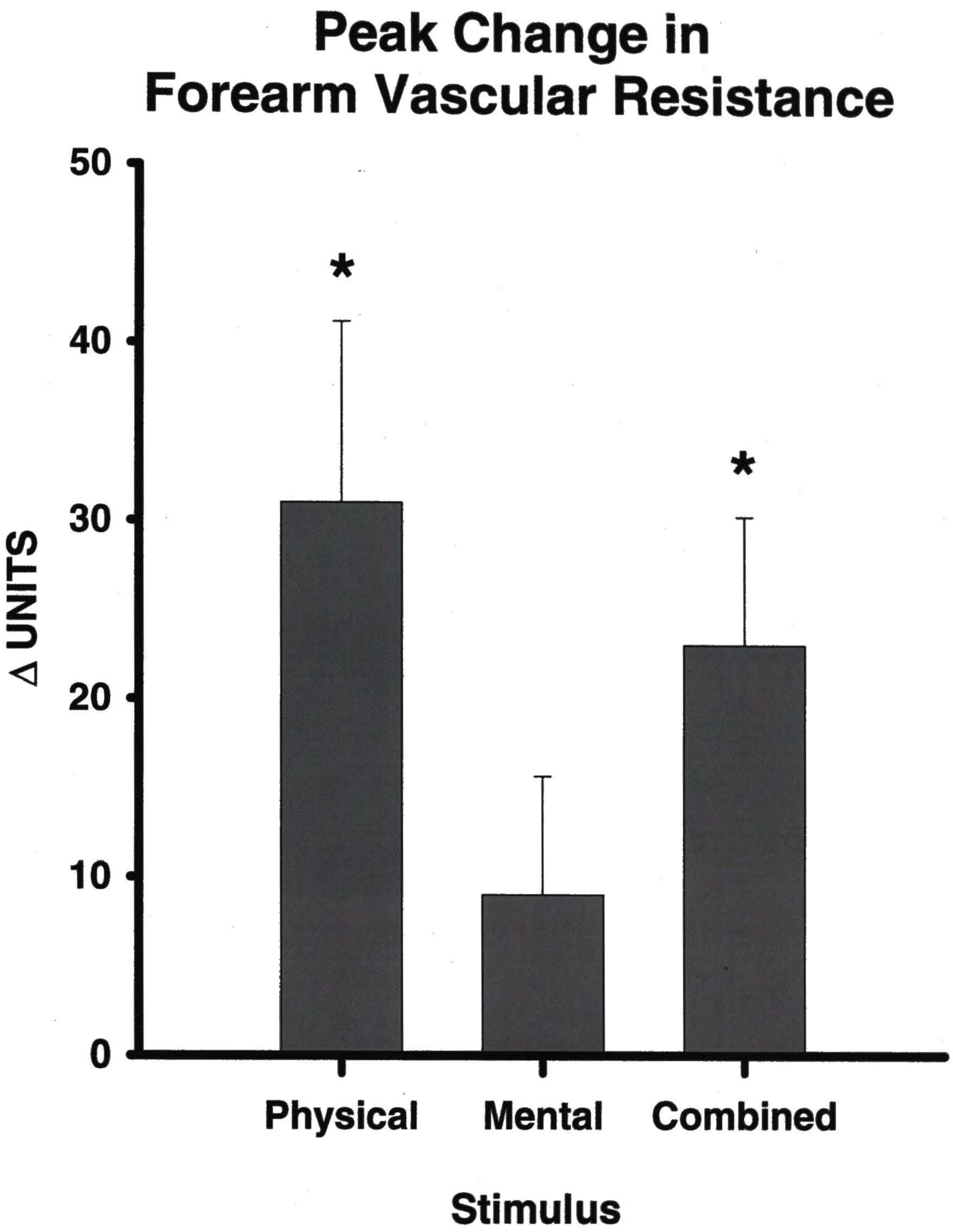


Figure XI. - The mean peak (±SEM) forearm vascular resistance (FVR) measurement for the three stress stimuli. *p <0.05 vs. baseline

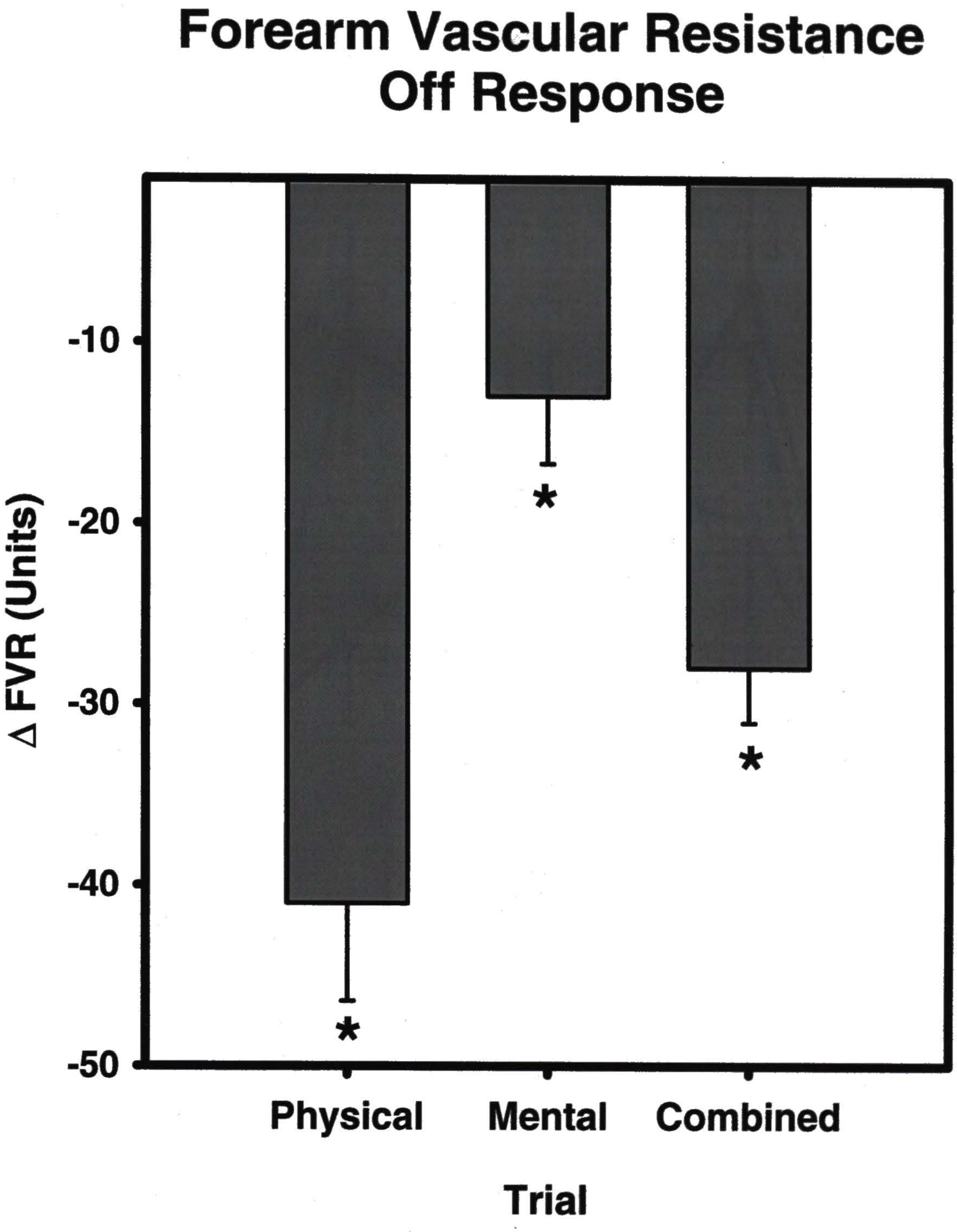


Figure XII. - Mean (±SEM) forearm vascular resistance (FVR) for the off response of the three stimuli. This was measured as a change from the end of stimulus to one minute of recovery. *p <0.05 vs. minute 5

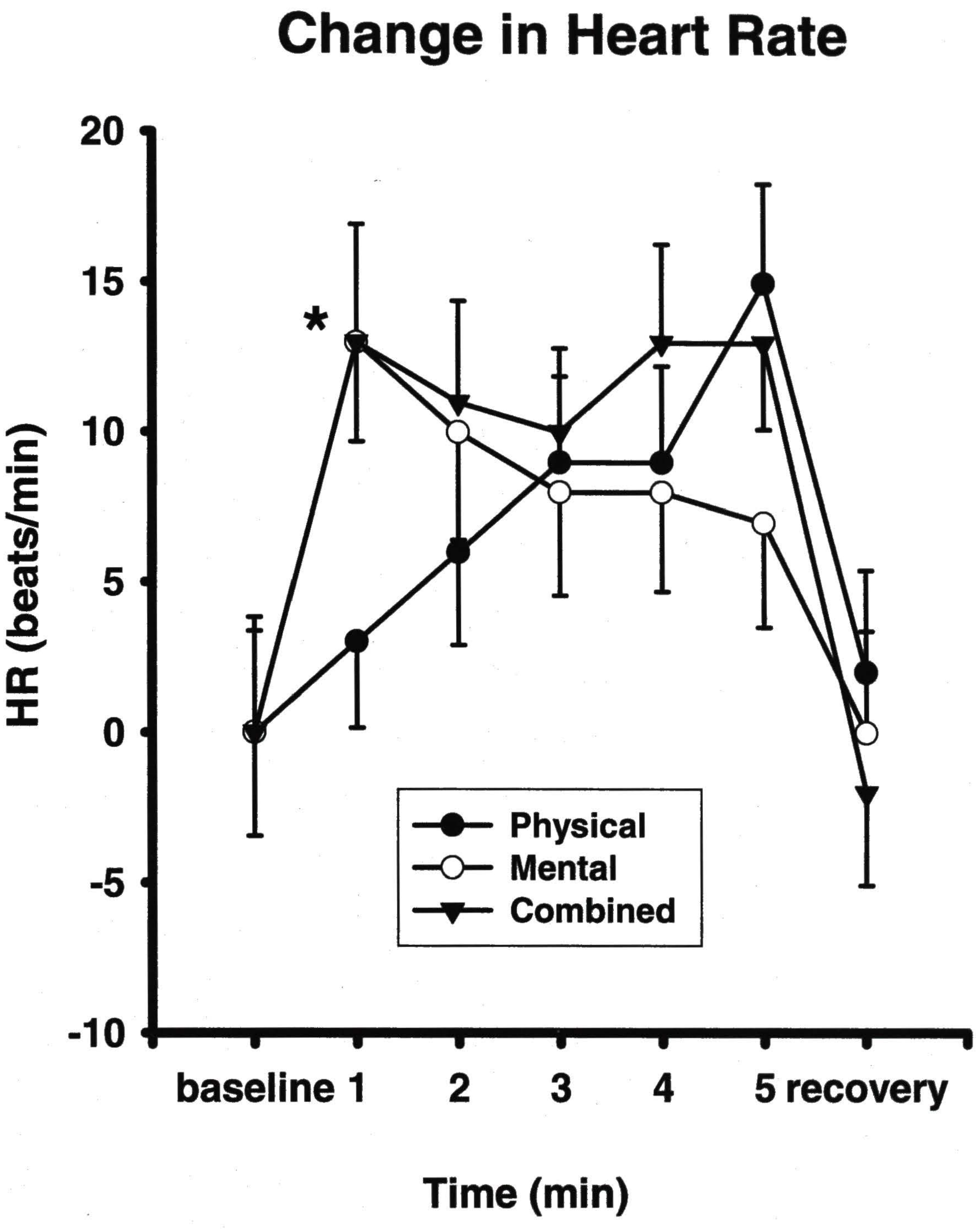


Figure XIII. - Mean (± SEM) heart rate (HR) data obtained from the three stress stimuli. * $p < 0.05$ vs. baseline

CHAPTER IV

DISCUSSION AND SUMMARY

The major finding of this study is when physical and mental stressors are combined in humans, the physiological response is comparable to the physical stress alone. Thus, the data refute the original hypothesis that a synergistic interaction between the stressors will be observed. The data instead suggest that there is a redundant interaction. This interaction would result in a physiologic response most similar to the physical activity of isometric contraction since its effect produces the greatest increase in the measured variables. This redundant interaction is attributed to a mutual inhibition of responses such that the net response to the combined stimuli is approximately the same as the greatest of the two individual stimuli (2). The nature of this interaction and its physiological relevance are discussed below.

Responses to Mental Stress

Cannon and Selye described mental stress as a disruption in the homeostasis of the body that elicits a physiological response (6,7,31). The response pattern typically includes an increase in blood pressure, heart rate, sympathetic nerve activity, and skeletal muscle blood flow (3,6,7,28). In this study, generally similar responses in these variables were observed. However, the responses to the mental task (arithmetic) varied widely among subjects. Some subjects responded with impressive changes in MAP (maximal individual response was 22 mmHg) and HR (maximal individual response was 36 beats per minute), whereas other subjects displayed minimal changes. Thus, this was a mild stressor for some subjects as is often observed with mental or psychological stressors. Individual psychological characteristics probably influence an individual's ability to deal with a mental stress and may contribute to the nature of the interaction with other stressors such as static exercise. This is discussed further below.

Response to Static Exercise

Isometric muscle contraction results in several physiologic adaptations that act to increase the delivery of oxygen and glucose, and flushing out unwanted metabolites (H^+, K^+, CO_2, and lactate) from muscle contraction. These responses are mediated by increased blood flow. This hyperemia is partly due to increased cardiac output, however, it is primarily the result of smooth muscle vasodilation in arterioles supplying the muscle microcirculation (27). Muscle metaboreceptors are located in the skeletal muscle (29). These receptors respond to the release of metabolites during exercise (H^+, K^+, and adenosine) which activate afferent nerve signals to the brainstem. These reflex signals primarily provoke increases in efferent sympathetic nerve activity leading to a pressor effect as observed by increases in vascular resistance and arterial pressure (29). The combination of these reflex responses and the central command signals from the central nervous system account for the net cardiovascular responses to static exercise. During sustained static handgrip, vascular resistance, sympathetic nerve activity, and mean arterial pressure do not increase substantially until the exercise is sustained for more than around one min (29). This pressor response then increases progressively as the exercise is sustained to fatigue. Our data are consistent with this response. The pressor response began to occur during the second minute and increased to a peak when the exercise was stopped after five minutes.

The protocol for this study permitted five second breaks in the middle of the isometric exercise. Subjects required the break in order to maintain the desired level of their maximal handgrip. The break might raise concern about its effect on the results of the experiment. For example, this may change both the central command and muscle metaboreceptor stimuli that provoke the physiologic responses explained above. The break temporarily eliminates the central command stimulus and allows for brief muscle hyperemia that would presumably wash out some built up metabolites (27). The data indicated that both MAP (Figure I) and SNA (Figure III) were similar between the second and third minutes of exercise, that is, immediately before and after the break. This suggests that the stimuli were temporarily reduced but the responses did not return to baseline levels. The pressor response then increased progressively during the fourth and fifth minutes of exercise until the exercise ended. Therefore, the data indicate that the handgrip stimulus can be considered continuous for the duration of the five minute exercise. The net trends regarding the interaction were similiar at minutes two and five. This leads to the conclusion that the break did not appear to confound the goals or conclusions of the study.

Time Course of Responses

The graph of the MAP shows an apparent biphasic response over the duration of the experiment. During the first three minutes, all three stimuli produce similar physiological responses. At the fourth minute of the experiment, there is a dramatic increase in the physical and combined responses of MAP, while mental MAP values appear to reach a plateau. After the fourth minute, the effects of physical activity continue to increase linearly. During this same period of time, the combined stimulus does not produce as dramatic of an effect. Although the interaction is not significant, there appears to be a redundant/inhibitory effect on the change in MAP of physical stress induced by the mental stimulus (Figure I).

Similar to MAP, SNA appears to be biphasic in nature throughout the experiment. During the first two minutes of the protocol, all three stimuli show similar increases in nerve activity. During the third minute of the experiment, the response to the physical stimulus became significantly greater than base line. After the third minute of the experiment, SNA produced by the physical stimulus continues to increase in a linear manner. As the nerve activity during the physical stimulus is increasing, the nerve activity during the mental stimulus is maintained constant. As seen in the changes of MAP, SNA during the combined stimulus is similar to that during the physical stimulus. The graded response over time and the peak SNA were not different between static exercise and the combined stimuli.

Measurements of the FVR among stimuli showed similar responses during the first three minutes of the experiment. At minute four significant changes were observed in the combined and physical stimuli (Figure X). The recovery data of vascular resistance indicated a significant difference during the off response in all three stimuli groups. The most interesting data during recovery indicated a significant difference between the physical activity and the combined stimuli. This result was unique to FVR and not observed in any other variable. The difference between the recovery rate of physical and combined groups was approximately equal to the mental FVR value. This interaction suggests that there was a possible additive effect. These results also may imply that mental stimulation act to aid in the recovery of physical activity. These subtle differences should be considered with caution since the individual variability was large; moreover, these differences were likely due, in part, to larger initial values (minute five of the stress) for the physical stress.

The results of this experiment imply that HR is not a good indicator of the effects prolonged by physical and mental stress. There was a significant response in HR from baseline in all three test groups; however, the data indicate no significant differences in HR between groups. Again, the HR data were quite variable and this variability likely contributes to the lack of differences. This lack of interaction may also be attributed to the fact that HR is an immediate response factor to stress stimulation irrespective of cause or origin and the variability of the data.

Possible Mechanisms of the Interaction

The interaction of the stimuli occurring in this experiment indicates a redundancy or mutual inhibition as described in the introduction. One explanation for this occurrence is neuronal redundancy. This mechanism is possible because intact humans function in a closed loop. A closed loop refers to the fact that a reflex response to one stimulus might affect the magnitude of another sensory afferent resulting in an altered end response. The responses to any stress are mediated by the autonomic nervous system, central command, and reflex input to the brainstem that converge on a few specific nuclei within the medulla. The net effect of a combination of stressors is importantly determined by the nature of neuronal interactions on these nuclei. Our data are consistent with a redundant interaction as described by Kezdi and Geller (2), in which the net efferent output is a function of the largest single input. Altering the activity of modulating neurons in the reflex might also affect the efferent signal sent to the end organ (2). As discussed in the introduction, the net physiological responses to several stimuli do not always interact in an additive manner. An exercising muscle elicits excitatory somatic responses as discussed in Chapter I; however, stimulation of baroreceptors and respiration can act as an inhibitory influence (2). This example of a closed loop suggests the inhibitory effect that mental stimulation can have in combination with isometric exercise.

An alternative mechanism could be that mental stimulation during sustained physical activity has a dampening effect on the efferent signal or can possibly act as a distracter to the pain associated with muscle fatigue and reduce the response that is secondarily related to pain. As the response to physical activity is maintained over time, there is an increased tendency to develop fatigue.

Fatigue of a muscle is a result of both peripheral and central factors. Peripheral fatigue occurs due to conduction and metabolic factors. When a muscle group is utilized at its maximal level, the conduction of action potentials, transmission at the neuromuscular junction, and metabolic byproducts become limiting agents (27). These limiting agents reduce the body's ability to maintain the force required overcome an afterload and perform external work. Central fatigue is the factor that controls the mental aspect of performance ability. This aspect allows the body not to utilize all motorneurons (27). Central fatigue can be demonstrated by contracting a muscle until it is fatigued then stimulating the same muscle for a twitch. If a twitch does occur the muscle was not utilized to its full capacity. Central fatigue, therefore, can explain how a well-motivated or encouraged individual can work a muscle longer due to the individual's ability to cope with fatigue and utilize the whole muscle group by recruitment of motorneurons. This concept of central fatigue can help explain how a mental distraction could potentially lower the physiological effects that occur in the body during isometric exercise. As the results of this study indicate, mental distraction acts as a controllable factor of fatigue. The use of mental distractions can potentially aid in limiting the effects of peripheral fatigue.

Summary

This experiment was designed to determine the interaction that occurs between mental and physical stimuli and the effects that this interaction has on cardiovascular responses and sympathetic nerve activity. It was hypothesized that there would be a synergistic interaction occurring between these stimuli. The primary conclusion of this experiment refuted the hypothesis and indicated that a redundant interaction occurred between the two stimuli. A possible explanation for this finding is the interaction of modulating neurons between the cardiovascular center of the medulla and the mental stress area of the brain located in the amygdala. Another factor that could be contributing to this redundant interaction is fatigue and its effects on physical exertion. Central fatigue could possibly act to inhibit the ability of a muscle group to contract due to insufficient muscle recruitment.

This experiment reveals that MAP, SNA, and FVR are the best indicators of the physiologic changes caused by physical and/or mental stimulation. These parameters appear to be uniquely sensitive to minute to minute changes in the body's response to the different stimuli. FVR recovery may indicate a mechanism by which mental stimuli act as a distracter from afferent signals coming from the tasked muscle group. However, the difference between the off responses of SNA during physical and combined groups due not support this conclusion. This is due to the fact that SNA is a major factor contributing to vessel diameter in the body, and there were no significant differences between the off response of the different groups.

Future Experiments

These results suggest that certain stimuli may differentially affect the performance and fatigue of specific task muscle groups. Perhaps unique mental stimuli can be found using the techniques and measurement methods of this thesis to cause a specific positive performance. Efforts can be made to target unique task muscle groups, such as forearm/upper torso muscles used almost exclusively for equipment assembly activities in zero gravity.

The results of this experiment indicate that mental stimuli/stress affect performance as measured by a percentage of subject's maximum handgrip in isometric exercise. Mathematical tasks appear to reduce the effects of physical stress and recovery time as indicated by FVR.

Future studies sponsored by National Aeronautics and Space Administration (NASA) should explore the effect of different types of mental stimuli at longer periods of time. Subjects have different levels of stress that they are capable of functioning under, therefore, future experiments should try to elicit a significant response in every subject. Extending the duration of the study will enable the investigator to further evaluate the inhibitory effects of mental stress on isometric exercise. The different influences of mental stimuli and/or instruction during work and/or during rest periods should also be investigated.

By increasing the duration of the stimuli, one should be able to detect changes that would occur over a longer period of time. For example, the results in MAP at minute five, where physical stimuli alone increases MAP in a linear manner and mental/physical combination results in decreased effects, require additional study of the time period after minute five. If mental stimulation does have a dampening effect on MAP, there may be a positive effect of fatigue reduction. However, the effect of SNA on FVR should be evaluated further in order to substantiate this claim.

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