OULU 2006
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ACTA
UNIVERSITATIS OULUENSIS

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HUMAN COLD EXPOSURE, ADAPTATION AND PERFORMANCE IN A NORTHERN CLIMATE

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HUMAN COLD EXPOSURE, ADAPTATION AND PERFORMANCE IN A NORTHERN CLIMATE

Academic Dissertation to be presented with the assent of the Faculty of Medicine, University of Oulu, for public discussion in the Auditorium of Kastelli Research Centre (Aapistie 1), on June 2nd, 2006, at 12 noon

OULUN YLIOPISTO, OULU 2006

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Acta Univ. Oul. D 876, 2006

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ISBN 951-42-8088-1 (Paperback)
ISBN 951-42-8089-X (PDF) http://herkules.oulu.fi/isbn951428089X/
ISSN 0355-3221 (Printed)
ISSN 1796-2234 (Online) http://herkules.oulu.fi/issn03553221/

Cover design
Raimo Ahonen

OULU UNIVERSITY PRESS
OULU 2006

Mäkinen, Tiina M., Human cold exposure, adaptation and performance in a northern climate
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Acta Univ. Oul. D 876, 2006
Oulu, Finland

Abstract

The purpose of the study was to examine the amount of cold exposure and factors affecting it at the population level in Finland, to determine what type of cold acclimatisation, if any, develops in urban residents in winter, and to find out whether cold acclimatisation or acclimation has a functional significance on psychological or physical performance. Tasks of low physical activity requiring attention and concentration (cognition, postural control) were assessed in cold.

In a cross-sectional population study Finns aged from 25 to 74 years (n=6,951) were queried of their wintertime outdoor exposure duration and factors affecting it. In experimental studies seasonal cold acclimatisation (thermal responses) and its effect on cognition were assessed in the laboratory, where 15 young urban subjects were exposed to cold in winter and summer in bright or dim light. A controlled cold acclimation trial (n=10) was performed to study the effects of repeated exposures to cold on cognitive performance and postural control in young urban subjects.

In the Finnish population the average amount of cold exposure in winter represents 4% of the total time. Most of the cold exposure occurs during leisure time and in outdoor occupations (agriculture, forestry, mining, industry, construction). Factors explaining increased occupational cold exposure were: occupation, age and a lesser amount of education. Factors associated with more leisure-time cold exposure were: being employed in outdoor occupations, being a pensioner, housewife, unemployed, practising physical exercise, and reporting at least average health. The experimental studies showed seasonal differences and aggravated thermal responses in urban residents in winter, but did not detect habituation responses typical of cold acclimatisation. In both seasons, acute moderate cold exposure resulted in positive, negative or mixed effects on cognition, reflected as changes in response times and accuracy. Simple cognitive tasks were impaired in cold, and in complex tasks both negative, positive and mixed effects were observed. It is suggested that cold exposure affects cognition through different mechanisms related to either distraction or arousal. Cold exposure increased postural sway by 70-90%, suggesting impaired postural control. Repeated exposures to moderate cold, reducing stress and discomfort and dampening physiological responses, did not markedly affect cognitive performance or postural control.

Keywords: acclimation, acclimatisation, body temperature regulation, cognition, cold climate, cold exposure, population, postural control, seasons

Science is not a mechanism but a human progress, and not a set of findings but the search for them (J.Bronowski: Science and human values)

Acknowledgements

This work was carried out at Kastelli Research Centre in Oulu, Finland. The institutes participating in the studies were: the Centre for Arctic Medicine, Thule Institute at the University of Oulu, the Finnish Institute of Occupational Health, Oulu, the Department of Physiology at the University of Oulu and the School of Social Work at the University of Southern California. The Graduate School of Circumpolar Wellbeing, Health and Adaptation, co-ordinated at the University of Oulu supported my research in various ways. During this study I had the opportunity to rely upon the expertise, experience and aid of several colleagues and friends whose impact on this study is acknowledged below.

My most grateful acknowledgements go to my supervisors. I want to express my special and sincere thanks to Emeritus Professor Juhani Hassi, who I consider has been a true mentor in my working career. Our co-operation with Juhani started within the field of applied cold research and development work. Juhani taught me that almost everything is achievable if one truly wants it. While working together we have achieved many magnificent results, which have felt most rewarding and motivating. Coming to work has never felt to be an obligation, which I consider is a privilege. In addition to helping me to grow and become much of the person I am today, Juhani is acknowledged for his obvious expertise in cold-related health issues. I am happy that we are continuing our fruitful collaboration and facing new challenges.

Professor Hannu Rintamäki initially introduced me to the research area of human thermoregulation and cold physiology while giving a lecture at the Department of Biology, where I was studying at that time. I was inspired by the topic and Hannu guided me through the earlier phases of my research career. I was happy to continue co-operating with Hannu some years later when engaging in my doctoral studies. Throughout our collaboration he has been highly supportive, motivating and knowledgeable. His door has always been open for me to ask all types of questions.

I want to express my sincere thanks to Professor Lawrence Palinkas from the School of Social Work at the University of Southern California, who I have been privileged to been supervised by. He has introduced me to the fascinating world of applied cognitive psychology. Larry has always given constructive comments and invaluable support, both when planning and implementing the different studies, as well as when preparing the manuscripts. Each of his visits to Oulu has given our entire research team additional motivation and ideas. Through our collaboration it has also been fascinating to get acquainted with and gain a vision of a foreign scientific community, and with the research Larry has conducted in Antarctica.

Many thanks are directed to my colleague Tiina Pääkkönen, M.Sc., for our co-operation and friendship. Together with Tiina we have spent numerous hours in the laboratory (days and nights) conducting the measurements. During these long stretches a special type of humour was developed. Conducting the studies together has also enabled us to share common questions and concerns.

I want to separately thank Emeritus Professor Juhani Leppäluoto for his co-operation in this series of studies. He has been most supportive and given feedback. His extensive knowledge on human cold physiology is acknowledged.

Several people have provided comments of this thesis. First, I want to express my sincere gratitude to the reviewers of this thesis, Dr. John W Castellani from the US Army Research Institute of Environmental Medicine and Professor Thomas F. Oltmanns from the Department of Psychology at Washington University for their expert comments. I also want to thank Emeritus Professor Juhani Leppäluoto, Dr. Hannele Säkkinen, Dr. Juha Oksa, Tero Mäkinen, M.Sc. and Tiina Pääkkönen, M.Sc. for their valuable and knowledgeable feedback.

I want to thank my co-authors, Professor Simo Näyhä, Dr. Dennis Reeves, Dr. Juha Korpelainen, Dr. Juha Oksa, Dr. Mika Rytkönen, Ville Kampman, M.Sc., Jari Jokelainen, M.Sc., Veli-Pekka Raatikka, M.Sc., and Reija Ruuhela. M.Sc. for their collaboration and expert knowledge. Jari Jokelainen from the Department of Public Health Sciences and General Practise is separately acknowledged for his expertise and support with the statistical questions.

My gratitude goes to the staff at the Centre for Arctic Medicine/Thule Institute. The centre has managed to employ persons who are all ambitious, knowledgeable and also very nice persons to work with. Hannele, Jaana, Mika, Simo and Sanna, many thanks to all of you for your support, the nice mementos, and our joint success. Thanks also to the Director, Dr. Arja Rautio for providing a supportive environment for finalising my studies.

Another working community I have shared is the staff working at the Finnish Institute of Occupational Health, Oulu. There are several friends and colleagues there that I have spent a great time with. Juha, Sirkka, Tuija, Jukka, Erja, Eeva, Maire and others, thanks for the collaboration and for the numerous lunch breaks which have been spent laughing rigorously. Warm thanks to librarian Tuula Vauhkonen, M.Sc., who purchased the literature information for me while preparing the synopsis. All my friends are also warmly acknowledged for providing additional content to my life besides work.

I want to thank my parents Erkki and Sirkka for their support and unconditional love throughout my life. Thank you for being the best parents one could ever have. Finally, my deepest gratitude goes to my family, Santeri and Tero, who have supported my work throughout these years. Santeri, you have been more than I could have ever hoped for. I can only continue to aim at being the best possible mother for you.

This work was supported by the Graduate School of Circumpolar Wellbeing, Health and Adaptation through a grant from the Finnish Ministry of Education.

Oulu, 20. April 2006 Tiina M Mäkinen

List of abbreviations and definitions

A	adrenaline ($ng \cdot ml^{-1}$)
BP	blood pressure (mmHg)
BMR	Basal metabolic rate ($W \cdot m^{-2}$)
CDT	cold detection threshold (°C)
CIVD	cold induced vasodilatation
clo	clothing insulation value (clo)
CNS	central nervous system
DBP	diastolic blood pressure (mmHg)
EMG	electromyography
HR	heart rate (beats/min)
M	metabolic heat production, metabolic rate ($W \cdot m^{-2}$)
NA	noradrenaline ($ng \cdot ml^{-1}$)
Q	heat content, body (J), the product of the body mass, its average specific heat and the absolute mean body temperature
Q_f	finger blood flow (perfusion units, PU)
RT	response time (ms)
SAD	seasonal affective disorder
S	storage of body heat ($W \cdot m^{-2}$) (positive=increase in body heat content, negative=decrease in body heat content)
SBP	systolic blood pressure (mmHg)
T_a	ambient temperature (°C)
T_b	mean body temperature (°C)
T_f	finger temperature (°C)
T_{rect}	rectal temperature (°C)
T_{sk}	mean skin temperature (°C), usually measured from 10-14 different sites in cold
TRP	transient receptor potential
TNZ	thermoneutral zone
VO_2	oxygen consumption (absolute: $l \cdot min^{-1}$, relative: $ml \cdot min^{-1} \cdot kg^{-1}$)
VO_{2max}	maximal oxygen consumption (absolute: $l \cdot min^{-1}$, relative: $ml \cdot min^{-1} \cdot kg^{-1}$)
WDT	warm detection threshold (°C)

List of original papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I Mäkinen TM, Raatikka VP, Rytkönen M, Jokelainen J, Rintamäki H, Ruuhela R, Näyhä S & Hassi J Factors affecting outdoor exposure in winter: population-based study. Int J Biometeorol, in press.

II Mäkinen TM, Pääkkönen T, Palinkas LA, Rintamäki H, Leppäluoto J & Hassi J (2004) Seasonal changes in thermal responses of urban residents to cold exposure. Comp Biochem Physiol Part A 139: 229-238.

III Palinkas LA, Mäkinen TM, Pääkkönen T, Rintamäki H, Leppäluoto J & Hassi J (2005) Influence of seasonally adjusted exposure to cold and darkness on cognitive performance in urban circumpolar residents. Scand J Psychol 46: 239-246.

IV Mäkinen TM, Palinkas LA, Reeves DL, Pääkkönen T, Rintamäki H, Leppäluoto J & Hassi J (2006) Effects of repeated exposures to cold on cognitive performance in humans. Physiol & Behav 87(1): 166-176

V Mäkinen TM, Rintamäki H, Korpelainen JT, Kampman V, Pääkkönen T, Oksa J, Palinkas LA, Leppäluoto J & Hassi J (2005) Postural sway during single and repeated cold exposures. Aviat Space Environ Med 76(10): 947-953.

Some unpublished results will also be presented in the thesis.

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1 Introduction

The Arctic and adjacent areas situated in the vicinity of the poles can be characterised in several ways. The Arctic may be defined as areas located near or above the Arctic or Antarctic circles (60-66 N and below 66 S), areas with permafrost, or situated beyond the tree line. Less specified definitions exist for circumpolar, northern, or high latitude environments. The circumpolar areas are defined as being located near the poles, but no strict limitations for geographic latitude are given. It could be defined as an environment having unique environmental, social, cultural and economical characteristics that are common to the area in question, but different from the surrounding environment. The circumpolar environmental conditions are characterised by considerable fluctuations in temperature and photoperiod meaning long, cold and dark winters and short, cool but bright summers. It is estimated that approximately four million people live in the Arctic (Bogoyavlenskiy & Siggner 2004) and more than 280 million in the circumpolar regions (Reed *et al.* 2001). It is evident that circumpolar inhabitants are exposed to cold in significant amounts in their everyday life.

The definition of cold depends on the perspective from which it is examined. From a physiological point of view, cold is the environmental temperature activating the human thermoregulatory system. This activation leads to physiological responses which may be either harmful or beneficial for a person's wellbeing. From a psychological perspective cold can be defined as the temperature which causes cold sensations or discomfort to an individual. Both the physiological and psychological aspects are included in the criteria of cold work, which is in occupational safety and health standards set to temperatures of 10 to 15°C (BS7915, DIN33405). On the other hand, from a behavioural perspective "cold" could be any ambient temperature below 20°C where unsafe occupational behaviour starts to increase (Ramsey *et al.* 1983). Finally, when viewed from a population health perspective, cold can be defined as an environmental temperature, for example 18°C (Europe) or 14°C (Finland), below which a linear increase in mortality is observed (The Eurowinter Group 1997). In Europe the number of days per year when the mean daily temperature is below this temperature is 200-360. In Finland, located between 60-69°N, the number of days when the daily mean temperature is below 0°C is between 90 to 220 days (3-7 months), depending on the region. Thus, it is reasonable to say that cold is present to a considerable amount in the everyday life of residents living in northern Europe.

People are encountered with cold exposure during their occupational activities, while commuting to work or during their leisure time. In some occupations, like in the mining industry, construction work, agriculture, forestry or seafaring, cold exposure may be considerable, lasting for several hours at a time. Military personnel performing their service may frequently be faced with harsh environmental conditions during their winter training manoeuvres. A substantial number of people also work in cold indoor occupations, mainly in the food processing industry. Cold exposure may also be significantly present during various leisure-time activities performed outdoors. It is characteristic of outdoor cold exposure during occupational and leisure-time activities that it fluctuates markedly and can be further aggravated by wind and precipitation. Other characteristics of the wintertime are snow, ice, and a reduced amount of light, which modify the environment and the risks associated with it.

Why is it important to study the effects of cold? Cold exposures have been shown to result in various adverse consequences on human performance and health. At its mildest cooling causes unpleasant sensations and thermal discomfort. Discomfort may be a distraction factor reducing the performance of tasks requiring concentration and vigilance, and it may thus increase the risk of accidents and injuries both in occupational and leisure-time activities. Cooling of the tissues may result in decreased physical (Oksa 1998) and mental performance (Palinkas 2001). Hence, extra effort may be needed to complete the same task compared to a warm environment. This leads to lowered occupational efficiency, for example. Decreased physical performance may also itself increase the risk of accidents and injuries. Cold exposure may be a triggering factor for certain diseases (cold urticaria, Raynaud's phenomenon) (Lehmuskallio *et al.* 2002, Reilly & Snyder 2005) and aggravate the symptoms of prevailing chronic diseases. Recent reports have indicated that everyday cold exposure is associated with several different complaints and symptoms (Rytkönen *et al.* 2005). It is also well known that the coldest season is associated with increased morbidity and mortality (The Eurowinter Group 1997, Näyhä 2005). Finally, if the cooling of the body is severe enough, cold injuries (frostbites, hypothermia) may occur. Thus, it is reasonable to claim that cold exposure is a significant health risk.

As with other stressors, humans can also adapt to living in cold environmental temperatures. Thermal adaptation may partially be genotypic, a result of long-term genetic selection (Taylor 2006). However, much of the reported adaptation to cold is phenotypic, i.e. occurring rapidly and within a lifetime of the human being. In fact, the majority of thermal changes related to repeated exposures to cold occur within a couple of weeks (Rintamäki 2001). Physiological adaptation due to repeated exposures to cold is a neural process including changes mainly in circulation and endocrine organs. A substantial portion of cold adaptation is behavioural, including seeking shelter, using protective clothing or improving housing (indoor heating).

The present thesis describes how modern people are exposed to cold at the population level, and examines whether thermal acclimatisation to cold occurs among urban people. The study also assesses the functional significance of cold adaptation (acclimatisation and acclimation) on selected measures of performance.

2 Review of the literature

2.1 Human thermoregulation

2.1.1 The thermoregulatory system

In terms of thermal physiology man is a tropical mammal. For a naked resting man the thermoneutral zone (TNZ) is relatively narrow, between 25-27°C (Erikson *et al.* 1956). The TNZ indicates the range of ambient temperature at which temperature regulation is achieved without regulatory changes in metabolic heat production or evaporative heat loss. In this temperature range heat fluxes are controlled via changes in cutaneous vascular tone. Humans are also tachymetabolic homeotherms, which mean that the cyclic variation in core temperature (circadian, seasonal) is maintained within a relatively narrow range. The core temperature is maintained at ca. 37°C, with a circadian fluctuation of 0.5-0.7°C. The temperature of the deeper areas of the body varies only to a minor extent with changes in environmental temperature. In contrast, the temperature of the skin, and especially the extremities, shows greater variation associated with environmental temperatures. The human thermoregulatory system is comprised of four main components: 1) thermoreceptors, 2) neural pathways mediating afferent and efferent information to and from the central nervous system (CNS), 3) the controlling system located at the CNS, and 4) the thermoeffector system.

The thermoreceptors are thermosensitive neural elements (nerve endings) reacting to an increase or decrease in temperature (see chapter 2.1.4.). The thermoreceptors are located in different areas of the skin, but also in the deeper parts of the body, like in the vicinity of blood vessels (carotid artery), some internal organs, skeletal muscle and in the CNS (midbrain, medulla oblongata, hypothalamus) (Hensel 1981). The sensory information from the thermoreceptors is transmitted via the spinal ganglion and the dorsal root to the spinal cord. From the dorsal horn second-order neurons, spinal thermosensitive afferents are conveyed through the lateral spinothalamic and spinocervical tracts to the thalamus, where they project to third-order neurons. These third-order neurons project to the sensory and insular cortex. Thermosensitive afferent fibres of the face are connected to second-order neurons in the trigeminal nucleus of the medulla oblongata (Hensel 1981). In the CNS the dominant region for the control of temperature regulation is the hypothalamus, and especially the preoptic area (PA) of the anterior hypothalamus. Much of the afferent information is collected in the anterior hypothalamus and reticular formation. The anterior hypothalamus controls heat loss. The posterior hypothalamus participates in the regulation of vasoconstriction and shivering (McIntyre 1980).

The control of body temperature at the CNS is complex, and it seems that thermal signals may be integrated at several levels within the spinal cord and brain. Furthermore, both inhibitory and excitatory neurons participating in temperature regulation appear to exist (Boulant 1981). There has been debate as to what is the regulated variable, temperature and/or change in temperature (Bligh 1979), body heat content (Houdas *et al.* 1972) or the rate of heat outflow (Webb *et al.* 1978). Several system models for human thermoregulation have been proposed (e.g. Stolwijk & Hardy 1966, Bligh 1979, McIntyre 1980, Werner 1980). It is not fully established how the thermal information is sensed, integrated or processed and transferred to the effector system. Furthermore, the establishment of a "set-point" that controls thermoregulation is not fully understood, either. In temperature regulation this "set-point" may change temporarily due to interference with non-thermal variables or pathological influences (e.g. starvation, hydration, fever). Adaptation to cold may also change the set-point.

The efferent signals are mediated by the thermoeffector system involving either autonomic or behavioural responses to heat and cold which modify the rates of heat production and heat loss. Examples of autonomic thermoeffector responses are sweating, thermal tachypnea, shivering, non-shivering thermogenesis and adjustments of circulatory convection (vasodilatation and vasoconstriction). Behavioural thermoregulation means any coordinated movement by an individual aimed to establish a thermal environment that represents a preferred condition for heat exchange (moving to shelter, changes in posture, clothing, housing etc.) (IUPS Thermal Glossary 2001). Behavioural responses markedly affect human thermal environments.

2.1.2 Heat loss and production

Heat loss. Most of the heat produced by the body is transferred from the inner areas to the surface through convection (C) via the blood flow. Heat also flows through the tissues by conduction (K). This is referred to as internal heat flow.

External heat flow occurs from the skin to the environment through conduction, convection, evaporation (E) and radiation (R). A heat gradient between warm skin and a colder environment causes a heat flow from the skin to the environment. Conductive heat transfer is the net rate of heat transfer in a solid material or a non-moving gas or fluid down a thermal gradient. Conductive cooling occurs when touching cold materials, or while standing, sitting or lying on cold surfaces. Radiant heat exchange indicates the net rate of heat exchange by radiation between an organism and its environment. Its value is positive when heat is lost from the human to the environment, and negative when heat is gained. Radiative heat from the sun, or while working in the vicinity of hot objects, is a source of heat. The net rate of heat transfer in a moving gas or fluid is called convection. As mentioned earlier, C can occur between different parts of the body or from the body surface to the environment. Heat transfer through C may develop and be amplified by thermal gradients (natural C) and by forces such as wind or body movements (forced C). The sum of heat flows or heat fluxes by R, C and K from the body to the environment is called dry heat loss or sensible heat loss. Evaporative heat loss means the heat transfer from the body to the environment by evaporation of water from the skin and the surfaces of the respiratory tract. E may be either passive (i.e. water vaporising from respiratory surfaces during normal breathing or water diffusing through the skin and vaporising at the surface) or mediated through autonomic thermoeffectors (e.g. sweating or panting).

Based on the previously described heat loss mechanisms, cooling can be classified into 1) whole-body cooling (decrease in core temperature), 2) extremity cooling (only extremities such as the head, hands and feet are cooled), 3) convective cooling (wind-chill), 4) conductive cooling (due to contact with cold materials while touching cold objects, or when standing or lying on cold surfaces) and 5) cooling of the respiratory tract (especially pronounced during heavy exercise in cold weather during oronasal breathing) (Holmér 1994).

Peripheral vasomotor responses in cold. Vasoconstriction of superficial blood vessels is an efficient means of reducing heat loss from the skin surface to the environment. The response is mediated by the autonomic nervous system. During maximal constriction the heat conduction is reduced to about one third of the maximal value (5 $W{\cdot}m^{-2}{\cdot}°C^{-1}$) (Rintamäki *et al.* 2005). During vasoconstriction some blood is still allowed to flow in the more superficial parts, but most of the circulation is directed to the inner parts of the body. In the limbs, a counter current heat exchange system occurs, so that cool blood from the skin returns along the venae comitans (close to the artery), gaining heat as it returns to the body core. As a result of the increased heat loss and vasoconstriction, the skin temperature of the peripheral areas is reduced. After cooling for about 5-10 min and often at skin temperatures below 12°C a sudden vasodilation occurs. This phenomenon is called cold-induced vasodilation (CIVD). During CIVD blood flow to the extremities is increased and shows oscillatory changes, where changes in blood flow precede an increase in skin temperatures by ca. 2 min (Daanen & Ducharme 1999). Arterio-venous anastomoses are thought to play a major role in CIVD, and they are mainly located in the extremities (hands, fingers, feet) and the head region (lips, cheek, nose, ears). CIVD responses are influenced by environmental and individual factors (for a review see Daanen 2003). CIVD may temporarily increase the skin temperature of the peripheral areas and restore impaired manual performance. The rise in skin temperature is followed by a vasoconstriction and thus a cyclic change in skin temperature, the so-called ‘hunting response’, is observed (Lewis 1930).

Peripheral vasoconstriction in the cold increases the peripheral resistance and causes a rise of the mean arterial pressure, cardiac output, and stroke volume, with a consequent reduction in cardiac frequency (Stocks *et al.* 2004).

Heat production. Chemical processes such as the oxidation of carbohydrates and fat of the human body produce heat as a by-product to energy transformation and utilisation. Metabolic rate (M) indicates the rate of transformation of chemical energy into heat and mechanical work by aerobic and anaerobic metabolic processes. Most of the metabolic energy (>80%) is released as heat and about 0 to 20% is used for mechanical work (e.g. external work). The basal metabolic rate (BMR) of a standard person is estimated at 44 W·m^{-2} (men) and 41 W·m^{-2} (women) (ISO 8996). The approximate resting metabolic rate (RMR) (sitting or standing) of a medium-sized adult person in a thermoneutral environment is 65-120 W·m^{-2} (ISO 8996). The metabolic rate may vary, and it is related to environmental conditions, clothing and the level of activity, as well as several individual characteristics. Exercise increases heat production several fold. In heavy exercise M may be 5-10 times higher compared with RMR (ISO 8996). In cold environments the energy expenditure is increased due to the higher M, heavy winter clothing and possibly lowered physical performance efficiency. In laboratory conditions a decrease in the environmental temperature increases the energy expenditure of resting subjects. For example, a decrease from 27°C to 22°C increased energy expenditure on average by 156 kJ·°C^{-1}, and from 22°C to 16°C on average by 116 kJ·°C^{-1} (van Marken Lichtenbelt *et al.* 2001, Westerterp-Plantenga *et al.* 2002). Eating increases M for some hours, and the effect of a single meal is approximately 20% in excess of BMR (Karst *et al.* 1984, Cannon & Nedergaard 2004). The activation of the sympathetic nervous system or the pituitary-thyroid axis (Laurberg *et al.* 2005, Leppäluoto *et al.* 2005) also alters the rate of secretion of thyroid and adrenal hormones affecting M.

Cooling of the peripheral areas and other thermosensitive structures (chapter 2.1.1), stimulates the preoptic area in the hypothalamus from where efferent information via α-motoneurons is mediated to the muscles, causing an increase in thermoregulatory muscle tone. If the cooling continues, the thermoregulatory muscle tone is superimposed by microvibrations. Shivering is involuntary contractile activity of skeletal muscles, not involving voluntary movements or external work, and where the individual motor units of the muscles discharge asynchronously. In mild shivering, the contractile activity of the motor units is periodical, while in more severe shivering, it is continuous. This increases M 2-5 times above basal levels. The fuel for low-intensity shivering is primarily retrieved from lipids, whereas under high intensity shivering carbohydrates become dominant (Weber & Haman 2005).

The metabolic rate increases also through non-shivering thermogenesis (NST). NST is defined as heat production due to metabolic energy transformation by processes that do not involve contractions of skeletal muscle (i.e. shivering). In NST heat is generated through special uncoupling proteins (UCP-1) situated in the brown adipose tissue (BAT). BAT is richly innervated with sympathetic nerves. UCP-1 is a mitochondrial channel protein allowing the influx of protons into mitochondria and uncoupling oxidative phosphorylation. In this process, heat is produced instead of ATP. Relatively large deposits of brown adipose tissue can be found in newborns. However, in adult persons the heat production through NST is not very significant, but may be activated if the exposure to cold is chronic (Cannon & Nedergaard 2004).

2.1.3 Components of thermal balance

Thermal balance equation. The body heat balance equation is a mathematical expression that describes the net rate at which the body generates and exchanges heat with its environment (first law of thermodynamics). The unit is watt (W), often also expressed in relation to unit area of body surface ($W \cdot m^{-2}$)

$$S=M-(W)-(E)-(C)-(K)-(R)$$

where S=storage of body heat, M=metabolic energy transformation=metabolic rate, W=work rate, E=evaporative heat transfer, C=convective heat transfer, K=conductive heat transfer, R=radiant heat exchange. Therefore, for achieving a thermal balance the rate of transfer of heat from the surface to the environment must equal heat production.

Determinants. The four basic environmental variables affecting thermal balance are the ambient temperature, radiant temperature, air movements and humidity. Combined with metabolic heat production and clothing, these variables form the fundamental factors defining human thermal environments (Fig 1.) (Parsons 2003).

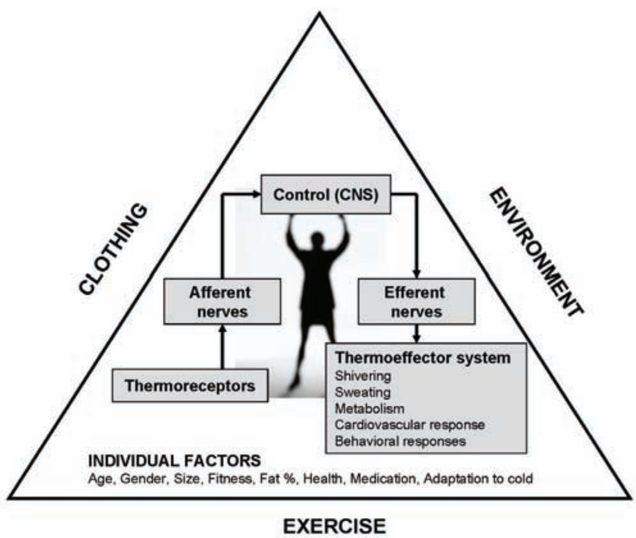

Fig. 1. The human thermoregulatory system and main factors affecting thermal balance.

Wind is a marked factor aggravating cooling under cold environmental conditions. The windchill equation (recently revised) takes into account the combined effects of temperature and wind and predicts the cooling of the bare skin (Wind Chill Temperature Index, http://www.nws.noaa.gov/om/windchill/). Radiation from the sun and different surfaces under sunny conditions is an external source of heat. In cold environments, moisture due to precipitation/snowfall may cause wetting of clothing, which decreases its insulation value and potentates cooling. Moisture may also originate from sweating, which also decreases the clothing insulation and enhances the heat loss. As the thermal conductivity of water is approximately 25 times that of exposure to cold air, heat loss is markedly increased by immersion into water. In addition to the type of exposure (air, water, wind), the intensity as well as the duration of the environmental exposure also affects the thermal balance.

Using appropriate cold protective clothing enables activities to be performed even under very cold environmental conditions. The need for thermal insulation varies depending on the environmental conditions and the level of activity (ISOTR 11079).

Several individual factors affect human thermal balance and the consequent thermal responses. These are: gender, age, size, fitness, and the amount of subcutaneous fat (e.g. Budd *et al.* 1991, Havenith *et al.* 1995, Van Ooijen *et al.* 2001, Stocks *et al.* 2004). Interestingly, also personality affects the autonomic nervous system responses and the subsequent thermal responses (Leblanc *et al.* 2003). It was observed that extroverts react more strongly to cold discomfort by increasing their heart rate and secretion of noradrenaline (NA) (Leblanc *et al.* 2004). Health may also affect thermal balance. For example, cardiovascular, endocrinological, muscular or neural disorders may significantly affect heat production and loss. Also, the use of certain medication and drugs may predispose subjects to cold. These are mainly drugs that affect the fluid balance, vasoconstriction and/or dilation and cardiac function. For example, certain drugs and medication may affect behaviour and predispose a person to the adverse effects of cold. Finally, thermal balance is markedly affected by behaviour (e.g. seeking shelter, clothing).

2.1.4 Thermoreception, thermal sensations and comfort

Thermoreceptors and thermal sensations. The thermoreceptors are free nerve endings and are either “cold” or “warm” types, according to their responses to stimuli. Recent knowledge suggests that the principal temperature sensors in the nerve endings belong to the transient receptor potential (TRP) superfamily of thermosensitive cation channels (Voets *et al.* 2004, Reid 2005). The thermoTRPs are activated by distinct physiological temperatures, and are involved in converting thermal information into chemical and electrical signals within the sensory nervous system. The main transduction mechanism for cooling occurs possibly via a cold- and menthol-activated ion channel (TRPM8). Stronger cooling activates another TRP channel named TRPA1 (ankyrin-like), which has been suggested to be related to cold nociception (Reid 2005). Four TRPV channels are activated by heating (TRPV1-4). It has been suggested that temperature perception, nociception and even tactile sensation may interact with each other (Green 2004). The thermoreceptors have a tonic firing pattern at comfortable skin temperatures, but respond to their specific stimuli. At constant temperatures, cold and warm receptors have characteristic temperatures for maximum static discharge frequency. For cold receptors, this ranges between 25 and 30°C, and for warm receptors between 40 and 47°C. A paradoxical discharge in cold receptors is also observed above 45°C. Both warm and cold receptors quickly become adapted when the temperature is kept constant (Kenshalo 1970, Hensel 1981).

A thermal sensation indicates how a person “feels”; it is at the same time a sensory experience and psychological phenomenon (Parsons 2003). The actual sensation is formed in the brain at the somatosensory cortex. The main determinants affecting the activation of the thermoreceptors and the subsequent thermal sensation are: 1) the number of receptors in a specific region (regional sensitivity) 2) the intensity of the stimulus, 3) adaptation temperature, 4) the rate of temperature change and 5) the size of the area stimulated (spatial summation) (Kensalo 1970, Hensel 1981). Stevens & Choo (1998) mapped the thermal sensitivities in different areas of the human body and found that it varies approximately 100-fold over the body surface. The face, especially near the mouth, is exquisitely sensitive. By comparison, the thermal sensitivity of the extremities and other regions is poor and intermediate, respectively. All body regions are more sensitive to cold than to warm. It was also found that with age, thermal sensitivity declines (Stevens & Choo 1998).

Thermal comfort. Thermal comfort is defined as the range of ambient temperatures within which a human in specified clothing expresses indifference to the thermal environment for an indefinite period (IUPS Glossary of terms for thermal physiology 2001). An overview of thermal comfort and determining factors is given by Parsons (2003). ISO 7730 provides assessment methods and principles for predicting thermal sensation and the degree of discomfort. In summary, thermal comfort is dependent on several environmental and individual factors. Fanger (1970) defines three conditions for a person to be in whole-body thermal comfort: 1) the body is in heat balance, 2) sweat rate is within comfort limits and 3) mean skin temperature is within comfort limits. Furthermore, absence of local discomfort is also required. Local cold discomfort may rise from draughts, thermal asymmetry or contact with cold surfaces (Parsons 2003). It should be noted that strong cold discomfort may be a significant distraction factor especially affecting tasks requiring vigilance and concentration.

The effect of thermal state on thermal sensations and comfort. Thermal sensations and comfort are related to the thermal state of the body. The influence of local sensation on overall sensation is different for different body parts. For example, cooling of the back and chest are dominant at influencing the overall sensation. Local thermal sensations may be influenced by the overall thermal state of the body (e.g. a local sensation is perceived as warm if the whole body is colder) (Zhang *et al.* 2004). In contrast, local cooling of hands and feet may produce a whole-body sensation of cold that is not related to the mean skin temperature. Arens *et al.* (2006) indicated that the overall sensations and comfort follow the warmest local sensation (head) in warm environments and the coldest (hands and feet) in cool environments. In some cases a reduction in core temperature, with a warm skin temperature, may be a sufficient stimulus for the sensation of cold (Cabanac *et al.* 1972). The correlation between thermal sensations, comfort and physiological responses under a steady-state environment deviates from transient conditions (Gagge *et al.* 1967, Zhang *et al.* 2004). Rapid shifts in environmental temperatures change thermal sensations and comfort before skin and core temperature are altered (Gagge *et al.* 1967), indicating that thermal sensations are affected by changes in heat flow. Zhang and co-workers (2004) provide models for local and overall thermal sensations and comfort for transient non-uniform thermal environments. Pellerin *et al.* (2004) assessed thermal comfort under heterogeneous but steady environments, and indicated that thermal discomfort is originated by the progressive recruitment of a certain number of body parts sensed as unpleasant.

2.2 Physical performance in cold

Cooling and physical performance. Physical performance is constituted of endurance (aerobic and anaerobic), muscular fitness (static and dynamic strength) and physical skills (velocity, balance, agility). Cooling of the muscle impairs most of its functional properties like power, force production and velocity (Faulkner *et al.* 1990, Oksa 1998). In dynamic work, the maximal force production and the power of short-term exercise decreases when muscles are cooled (Sargeant 1987, Comeau *et al.* 2003). Furthermore, the time to reach maximal force level and relaxation rate increases (Faulkner *et al.* 1990). It seems that especially fast movements are susceptible to cooling (Sargeant 1987, Oksa 1998). A dose-dependent relationship between the degree of muscle cooling (e.g. muscle temperature) and decrement in performance has been observed (Oksa *et al.* 1997). However, even a rapid lowering of the skin temperature (with a warm core temperature) may already decrease isokinetic maximal force production (Cheung & Sleivert 2004). The impaired power and force production of cooled muscles may be due to changes in their neuromuscular function, such as increased coactivation of muscle pairs (Oksa *et al.* 1995), changed reflex functioning (Oksa *et al.* 2000, Dewhurst *et al.* 2005) or altered nerve conduction velocity (Rutkove 2001).

Compared to dynamic exercise, static or isometric exercise is less susceptible to cooling. The effects of muscle cooling on static exercise vary, but it seems that a rather pronounced lowering of muscle temperature is required before performance decrements are observed. The decrement in maximal voluntary contraction ranges from 11 to 19% when the muscle temperature decreases below 27°C (for a review see Oksa 1998). Cooling can have a beneficial effect on sustained isometric exercises, slowing the rate of fatigue and increasing endurance time (Petrofsky & Lind 1980).

The abovementioned deficits in power and co-ordination related to cooling of muscles and nerves, combined with the complexity of human movements, are likely to result in impaired physical performance in the cold.

Postural control in the cold. Sufficient postural control is important for many daily activities. Impaired balance may result in decreased performance and injuries resulting from slipping, tripping or falling accidents. The cold environment itself, with icy surfaces and reduced amount of light during the winter, can endanger postural stability (Gao & Abeysekera 2004). Maintaining one's balance is a complex phenomenon. Postural control consists of sensory, neural and motor elements. Sensory information of the body's posture is gained through visual, somatosensory and vestibular systems. The afferent information is integrated at the spinal cord, medulla, midbrain, cerebellum and cerebral cortex. Finally, postural control is obtained by pre-programmed anticipatory postural adjustments, muscle reflexes, peripheral elasticity of muscles and tendons, as well as pre-programmed and voluntary corrections (Latash 1998).

Cold exposure may affect postural control through a variety of mechanisms. Firstly, cooling may affect the sensory systems involved in postural control. For example, cooling of the sole and ankle mechanoreceptors increases postural sway momentarily (Magnusson *et al.* 1990, Stal *et al.* 2003). Secondly, the proprioceptors located in the muscles, tendons and joints can also be affected by cooling, resulting in changes in neuromotor functions. Thirdly, cooling may also decrease the activity of the muscle spindles, leading to suppression of tendon-reflex amplitudes, consequently affecting neuromuscular control (Oksa *et al.* 2000). Fourthly, the neural transmission of both afferent and efferent information may be slowed due to cooling of the nerves (Rutkove 2001). Furthermore, the abovementioned impaired muscular function due to cooling (Oksa 1998) could render the fine-tuning of movements when maintaining balance more difficult. Finally, shivering may alter postural control due to an increased muscle tone. When cooling progresses, the muscle tone changes into shivering and is associated with visible shaking or shuddering. Shivering could cause perturbations in fine motor control (Meigal *et al.* 1998), requiring more tuning of movements compared with a warm environment.

Although cooling changes sensory, neural and muscular functions, their effect on whole-body postural control have not been examined. Multiple environmental stressors (cold, hypoxia, and fatigue) and postural control were studied during a disabled submarine simulation, but it was not possible to distinguish the effect of cold exposure in this study (Cymerman *et al.* 2002). It is also not clear whether cold adaptation affects postural control. It can be hypothesised that dampened shivering could result in a reduced need for corrective movements. It is also possible that the less intense cold sensations and reduced discomfort due to cold adaptation could improve concentration on maintaining balance.

2.3 Cognitive performance in cold

Mental performance plays a crucial role in the areas of orientation, safety, decision-making, work productivity and reactions to emergency situations. Cognition consists of basic learning (e.g. learning to read, write, calculate and acquiring skills) and applying knowledge (e.g. focused attention, reading, writing, problem-solving and making decisions). It is known that hot or cold environmental temperatures impair cognition. A meta-analysis suggested that cold exposure results in a greater negative effect on performance than hot exposure, and that a wet bulb globe temperature index of 10°C or less causes a 14% decrement in performance depending on exposure duration and type of task (Pilcher *et al.* 2002). Overall, cold exposure may adversely affect vigilance, concentration, memory (recognition and recall), reasoning and general intelligence (for a review see Palinkas 2001 and Hoffman 2001). The adverse effects of cold are demonstrated as an increased amount of errors and longer response times. The effects are dependent on the type of tasks (complex vs. simple), as well as the type (air or water) and duration of the cold exposures. A summary of the studies examining the effects of cold on various elements of cognition is given in Table A1 in Appendix 1.

It is well known that marked whole-body cooling associated with a reduction in core temperature by 2-4°C impairs cognitive functions, such as memory and concentration (Coleshaw *et al.* 1983, Giesbrecht *et al.* 1993, Lockhart *et al.* 2005). Eventually, if deep body cooling progresses below the level of hypothermia (35°C) symptoms of confusion, amnesia and decreased alertness and consciousness are seen. The results of moderate, non-hypothermic cold exposure on cognition are on the other hand inconsistent, so that decreased, unaltered or even improved cognitive performance has been observed (for a review see Palinkas 2001). The lack of consistency between these studies is probably due to differences in study designs (e.g. subject characteristics, type and duration of cold exposure, season, amount of repetitions and type of task). For example, with regard to task complexity it seems that the more complex the task, the more pronounced the adverse effects of cold (Ellis *et al.* 1985, Giesbrecht *et al.* 1993). With regard to the duration of the cold exposure, a recent study examined the effects of a long-term cold weather operation (9 days) on cognition and physical performance. It was concluded that with normal core temperature and hydration levels no serious decrements in cognitive performance were observed (Marrao *et al.* 2005). It is also possible that the rate of cooling may affect cognitive performance differentially, so that fast cooling may impair performance more than slow cooling (Ellis *et al.* 1985).

Two distinct theories on the effects of cold on cognitive performance have been proposed. The distraction hypothesis suggests that the discomfort caused by cold could consume central attention resources, causing a momentary switch of attention from the primary task and leading to impaired performance (Teichner 1958). There are some studies supporting the distraction hypothesis (e.g. Teichner 1958, Bowen 1968, Davis *et al.* 1975, Vaughan 1977). Another theory suggests that the general arousal level is increased by mild/moderate cold exposure, which initially leads to improved performance. However, with continued, prolonged or more severe cooling arousal may increase to a level where performance is degraded (Provins *et al.* 1973, Ellis 1982, Ellis *et al.* 1985, Enander 1987, Van Orden *et al.* 1990). Supporting the arousal theory, Van Orden *et al.* (1990) found shorter evoked potential latencies in the cold, suggesting faster CNS processing. Provins *et al.* (1973) measured EEG activity and found that arousal was highest when the subject was feeling most discomfort and shivering. On the other hand, FitzGibbon *et al.* (1984) indicated the EEG activity is significantly altered only when core temperature is hypothermic (33.5°C).

At present it is unclear whether season is associated with changes in cognition. Winter in high latitudes is characterised by a limited amount of daylight. The increased prevalence of depressive symptoms/negative mood states in winter was named seasonal affective disorder (SAD) by Rosenthal *et al.* (1984). The lack of light is known to trigger SAD and also to increase the occurrence of sub-clinical depressive symptoms (S-SAD) in winter. The prevalence of winter SAD ranges from 1 to 10% and winter S-SAD from 2 to 19% in North America and Europe, respectively (Mersch *et al.* 1999). Only a few studies have examined whether SAD is associated with cognition (O'Brien *et al.* 1993, Drake *et al.* 1997, Michalon *et al.* 1997), and some of these demonstrated that SAD was associated with impaired cognitive performance (O'Brien *et al.* 1993, Michalon *et al.* 1997). Mood states in general have a profound effect on information processing (Thayer 1989). Depression impairs or disrupts encoding processes that may lead to incomplete learning and memory (Weingartner *et al.* 1981).

Season could affect cognition through endocrinological changes as well. Cold exposure and a cold season are known to affect the hypothalamic pituitary-thyroid axis (Pääkkönen 2002, Leppäluoto *et al.* 2005), increasing the secretion of thyroid-stimulating hormone (TSH), which leads to increased thyroid hormone production and clearance rates (Reed 1995) and lower levels of free thyroid hormones. It appears that the cold-induced increased clearance rates of thyroid hormones lead to decreased levels of thyroid hormones that sensitise pituitary thyroid cells. This state is called the polar T_3 syndrome. These seasonal changes in thyroid hormones have been demonstrated in overwintering personnel in Antarctica (Reed *et al.* 1990, Reed 1995, Palinkas *et al.* 2001), as well as in residents living in northern Finland and employed in outdoor occupations (Leppäluoto *et al.* 1998, Hassi *et al.* 2001). The lowered levels of free thyroid hormones can lead to a state of sub-clinical hypothyroidism and to increased anxiousness and depression (Xu *et al.* 2003), which could impair cognition. A recent study demonstrated that anxiousness in hypothyroidism was related to attentional and executive disturbances (Constant *et al.* 2005). Further support for the assumption that cognitive performance is connected to season and decreased levels of thyroid hormones was provided by Reed *et al.* (2001). In their study, personnel overwintering in Antarctica showed a decline in cognitive performance after 11 months, but the effect was reversed with a thyroid hormone supplement. In addition, Shurtleff *et al.* (1994) demonstrated that administration of tyrosine significantly improved matching accuracy in cold.

The effects of cold adaptation on cognition have not been studied. Only few studies have repeated the cognitive tests in their study protocols (e.g. Thomas *et al.* 1989), but no specific emphasis was given to the effects of cold adaptation on cognitive performance. A reduction in stress and discomfort due to cold habituation may have a positive effect on cognitive performance due to reduced distraction.

2.4 Cold and health

A cold climate may be a significant health risk factor (Mercer 2003, Hassi 2005). Exposure to low environmental temperatures causes a variety of effects ranging from various symptoms to cold injuries and higher mortality. Increased prevalence of cold-related complaints and symptoms are observed when T_a falls below -15°C (Rytkönen *et al.* 2005). Cold may be an aetiological factor for certain diseases (e.g. cold urticaria, Raynaud's phenomenon) (Hassi *et al.* 2005) and it may also aggravate the symptoms of prevailing chronic diseases. For example, cold environmental temperatures worsens respiratory symptoms, especially in people having a chronic respiratory disease (e.g. asthma, chronic obstructive pulmonary disease) or who are smokers (Kotaniemi *et al.* 2002, Kotaniemi *et al.* 2003). Seasonal increases in morbidity from cardiovascular and respiratory diseases have been demonstrated in many studies (e.g. Spencer *et al.* 1998, Danet *et al.* 1999, Näyhä 2002, Hajat *et al.* 2004). Excess winter mortality is also a well-known phenomenon demonstrated to occur throughout the world (Gyllerup *et al.* 1991, Kunst *et al.* 1993, Eng & Mercer 1998, Kloner *et al.* 1999, Donaldson & Keatinge 2003). For example, an estimated 2,000-3,000 additional deaths occur annually in Finland during the cold season (Näyhä 2005). In Finland, mortality is lowest at 14°C (Näyhä 2005), and in the Mediterranean countries at about 22 to 25°C (The Eurowinter Group 1997), and a linear increase is observed below those temperatures. The seasonal variation in mortality appears to be lowest in countries with cold winters (McKee 1989). The main causes for the excess winter mortality are cardiovascular (e.g. coronary heart diseases, cerebrovascular diseases) and respiratory diseases (The Eurowinter Group 1997, Keatinge *et al.* 2000).

Cold environmental temperatures may either directly (cooling of the body) or indirectly (changed environment) increase the risk of accidents. Unsafe behaviour leading to accidents increases when the temperature deviates from 20°C (Ramsey *et al.* 1983). Cold-associated injuries are commonly strains and sprains resulting from slip and fall accidents. An association between cold temperature and an increased amount of occupational injuries in the mining industry in the USA was demonstrated by Hassi *et al.* (2000a).

A cold exposure which leads to freezing of the tissues causes frostbites (freezing injury). It is well known that the greatest prevalence of frostbites occurs during warfare (Paton 2001). However, frostbites are also common in civilian life (Hassi & Mäkinen 2000, Hassi *et al.* 2005). Several individual (e.g. peripheral vascular disease, earlier cold injury, psychiatric disorders, use of alcohol, medication, hydration level) and environmental factors (e.g. exposure duration, wind, moisture, contact with cold objects, latitude of residence) affect the frostbite risk (Rintamäki 2000, Ervasti *et al.* 2004, Castellani & O'Brien 2005). It should be noted that deep frostbites commonly cause different sequelae resulting in long-term symptoms and disability (Hassi & Mäkinen 2000). Cold may also cause non-freezing injuries (trench foot/immersion foot, hypothermia), which can in severe cases lead to peripheral nerve damage and tissue necrosis (Long *et al.* 2005). Accidental hypothermia is defined as an unintentional fall in core temperature below 35°C. It is a relatively uncommon problem affecting all age classes, but especially the elderly (Mallet 2002). An overview of its pathophysiology and treatment is given by Mallet (2002) and Giesbrecht (2000).

2.5 Definitions and types of human cold adaptation

2.5.1 Definitions

In the IUPS Glossary of terms for thermal physiology (2001) adaptation denotes the changes that reduce the physiological strain produced by stressful components of the total environment. This may occur within the lifetime of an organism (phenotypic) or be the result of genetic selection in a species or subspecies (genotypic). Phenotypic adaptation occurs when an organism modifies either its morphological configuration (e.g. amount of subcutaneous fat, fur thickness) or its physiological responses. Acclimatisation means the physiological or behavioural changes occurring within the lifetime of an organism that reduce the strain caused by stressful changes in the natural climate (e.g. seasonal or geographical). Acclimation means the physiological or behavioural changes occurring within an organism that reduce the strain caused by experimentally induced stressful changes in particular climatic factors. Habituation denotes the reduction of responses to, or perception of a repeated stimulation.

2.5.2 Types of cold adaptation

Young (1996) has suggested that habituation is the most common form of cold adaptation and develops in response to repeated cold exposures where whole-body cooling is not substantial. It seems that when repeatedly exposed to cold, the bodily system learns that the situation is not dangerous and there is no need for strong thermoeffector responses (LeBlanc 1992). When being habituated to cold, shivering and the vasoconstrictor response are blunted. At the same time stress responses are reduced, meaning a lesser rise in blood pressure (BP) and reduced release of stress hormones in the circulation. The blunted vasoconstriction and shivering may lead to greater fall in core temperature compared with non-habituated persons.

Whole-body acclimatisation responses in humans have been classified as 1) hypothermic, 2) insulative or 3) metabolic (Bittel 1992). A mixture of the previous types, for example insulative-hypothermic or metabolic-insulative responses have also been observed. The pattern of acclimatisation depends on the type and intensity of cold exposure as well as the previously mentioned individual characteristics.

In hypothermic cold adaptation, the core temperature is allowed to decrease more pronouncedly compared with non-acclimatised people before the heat production responses (shivering) are initiated. At the same time, the thermal conductance is less compared with non-acclimatised subjects. This is due to enhanced vasoconstriction and more considerable decrease in skin temperature, which preserves heat. It can also reflect lower metabolic heat production. The metabolic type of cold acclimatisation is characterised by increased M while exposed to cold. The insulative type of cold acclimatisation is associated with an enhanced vasoconstriction and consequent insulation which prevents cooling (Bittel 1992, Young 1996).

According to Young (1996), more pronounced physiological adjustments occur when repeated exposures to cold cause significant heat loss. Insulative adaptation to cold is believed to develop when M is insufficient to prevent cooling of the core. On the other hand, the metabolic type of adaptation is suggested to prevail when core cooling can be compensated by increased heat production (Young 1996). An alternative explanation for the determinants of cold adaptation is proposed by Bittel (1987), who suggests that the type of cold adaptation is dependent on the body composition, so that lean persons develop metabolic adaptation and less fit individuals develop insulative adjustments. Bittel further suggests that the amount of heat debt can be used as an index of cold adaptation.

Altogether, the cold adaptation pattern is dependent on several environmental and individual factors. Furthermore, genetic aspects and ethnic differences cannot be ruled out, although no conclusive evidence has been presented (Taylor 2006).

2.6 Acclimatisation to cold

2.6.1 Cold acclimatisation among indigenous people

Various indigenous populations have offered scientists a possibility to study the effects of cold acclimatisation on human thermal responses as early as in the 1950s (for a review see Radomski & Buguet 2002). This has laid a foundation for the current understanding of how humans can adapt to severely cold climates. Common characteristics of the indigenous populations are that the houses/shelters were very primitive or lacking and the protection provided by clothing poor. In many cases the cold exposure was intermittent and periodic, such as nocturnal cold temperatures.

One of the first native groups investigated were Australian aborigines who live in a semi-desert environment with average night temperatures of 4°C. They slept semi-nude and without shelter. Compared with non-acclimatised people, the metabolic and thermal responses of the aborigines showed no increase (but a slight decrease) in M and a greater drop in T_{rect}, T_{sk} and body temperatures. These responses suggest hypothermic insulative acclimatisation (Scholander *et al.* 1958a). The hypothermic response is beneficial in these climatic conditions since it saves energy when compared to the situation where core temperature is maintained.

Similar to the Aborigines, the Kalahari Bushmen wore little or no clothing, and were exposed to nocturnal temperatures as low as 0°C. When exposed to cold, the Bushmen did not shiver, showed only a small increase in M, and allowed their body temperature to drop (but not as low as the Aborigines). These responses suggest insulative acclimatisation to cold (Wyndham & Morrison 1958).

In contrast to the Aborigines and Bushmen, the Alacuf Indians of Tierra del Fuego were exposed to cold for 24-h being semi-nude. This population had a resting metabolic rate that was 160% higher than that of non-cold-acclimatised people. Otherwise, no major differences in rectal, body and skin temperatures were observed. This pattern of thermal responses suggests metabolic acclimatisation (Hammel *et al.* 1960).

One special group whose acclimatisation to cold has been studied are the pearl divers (AMA) from Korea. In their occupation, these women are immersed in cold water for several hours per day. It has been shown that repeated exposures to these conditions resulted in metabolic (higher BMR), insulative-hypothermic (lowered lower critical temperature) and local cold acclimatisation (vascular adaptation, lowered heat flux in limbs) (Hong 1973). It is noteworthy that the more recent use of wet suits abolishes the cold acclimatisation responses (Park *et al.* 1983, Hong *et al.* 1986).

The Arctic Indians of the Yukon and Arctic Inuit were intermittently exposed to cold while travelling, hunting and trapping. Furthermore, they were often well protected with Arctic clothing. The adaptation to cold was largely restricted to the extremities (e.g. hands) where higher skin temperatures were recorded (Irving *et al.* 1960, Elsner *et al.* 1960a, Elsner *et al.* 1960b, Hart *et al.* 1962). M was also higher compared with non-acclimatised people (but not as high as in the Alacuf Indians). The pattern of adaptation of the Inuit resembles metabolic acclimatisation. In contrast to the Inuit, the nomadic Lapps showed no increase in M but a pronounced drop in T_{rect}. This pattern, hypothermic insulative acclimatisation, resembles the responses of the Aborigines (Andersen *et al.* 1960).

Anthropologic studies examining the BMR of indigenous, northern circumpolar populations compared with non-indigenous people have been carried out recently (Galloway *et al.* 2000, Leonard *et al.* 2002, Snodgrass *et al.* 2005). A meta-analysis combining data from several circumpolar populations from North America and Siberia implicate that indigenous populations have a higher BMR, which is suggested to be due to both functional and genetic factors (Leonard *et al.* 2002). The higher BMR is suspected to be partially related to climatic influences (i.e. cold stress).

2.6.2 Polar expeditions

The cold acclimatisation responses of the personnel residing in Antarctica for defined periods have been examined in several studies (e.g. Budd & Warhaft 1966a, Budd & Warhaft 1966b, Wyndham & Loots 1969, Rivolier *et al.* 1988, Naidu & Sachdeva 1993). Compared with their regular daytime work, overwintering personnel of the Antarctic expeditions are often confronted with increased amounts of outdoor exposure to cold temperatures associated with field research. Ambient temperatures in Antarctica may be very low, even -70°C in the winter. The results of the different studies concerning thermal responses and cold acclimatisation have provided divergent results. The variation in the observed acclimatisation patterns can be attributed to differences in the length and severity of the exposures, individual characteristics, physical activity and the clothing used. Residents staying in Antarctica for 29 weeks and infused with NA after the expedition, demonstrated a lesser rise in BP, enhanced vasoconstriction and calorigenic response (Budd & Warhaft 1966a). On the other hand, four men working in Antarctica for 24 weeks showed an improved ability to maintain their T_{rect}, but showed no changes in shivering, skin temperatures or BP in response to a 2 h cooling test at 10°C (Budd & Warhaft 1966b). Obviously, individual characteristics also play an important role in what type of thermal responses are observed. Wyndham & Loots (1969) found that thin men developed thermal responses resembling those in men with more subcutaneous fat after the year in Antarctica (weight gain, reduced metabolic response, decreased skin temperature and increased T_{rect}). A more recent investigation where a whole-body cooling test was performed after a 53-day Antarctic expedition resulted in a delayed onset of shivering. In addition, local acclimatisation in terms of higher finger temperatures and lowered vascular resistance was observed (Rintamäki *et al.* 1993). Consistent with this observation, a reduction in sympathetic activity and stress hormones has been observed (Farrace *et al.* 1999, Farrace *et al.* 2003, Harinath *et al.* 2005). This would support cold habituation responses. Naidu & Sachdeva (1993) measured 64 tropical men after an 8-week stay in Antarctica and detected increased finger blood flow, but also a more pronounced vasoconstrictor response towards cooling. Similarly, enhanced vasoconstriction was observed in fingers of the personnel of an Australian research expedition after one year in Antarctica (Elkington 1968). Furthermore, no peripheral acclimatisation was observed in scuba divers working in Antarctica (Bridgman 1991). In summary, the divergent results from the Antarctic expeditions are explainable by the variation in the type and amount of cold exposure resulting in different thermal responses.

Acclimatisation responses during ski expeditions/journeys have also been recorded. In these studies the environmental conditions have varied markedly. A 63-day ski journey to the North Pole resulted in general hypothermic-hypometabolic cold adaptation (lowered T_{rect} and M, and increased local skin temperatures (Bittel *et al.* 1989). A ski journey across Greenland for 21 days resulted in hypothermic (lowered T_{rect}), insulative (decreased T_{sk}) and isometabolic (unaltered M) acclimatisation. At the same time also local cold acclimatisation (warmer foot temperatures) was observed (Savourey *et al.* 1992). Livingstone (1976) did not observe any peripheral acclimatisation among military personnel after a 2-wk stay in the Arctic where ambient temperatures ranged between -10 and -40°C. Also a depressed, rather than enhanced CIVD response was observed after a 2-wk journey (Livingstone *et al.* 1996). The variations in results and acclimatisation patterns can be attributed to differences in the length and severity of the exposures, the physical activity and the clothing used.

2.6.3 Cold acclimatisation in modern societies

Seasonal differences in thermal responses in modern populations have been reported in only a few studies. A common characteristic of these studies is that they have been mostly conducted in mild/moderately cold climates. In summary, the studies have provided different results concerning wintertime cold acclimatisation responses. A study conducted in the Netherlands, with a moderate oceanic climate (outdoor temperatures in winter above 0°C), observed an increased response in M in winter compared with summer when subjects were exposed to moderate (15°C) cold (van Ooijen *et al.* 2004). Seasonal thermal responses have also been assessed in Japanese subjects during mild cold exposure (10 to 15°C) (Lee & Tokura 1993, Li *et al.* 1994, Inoue *et al.* 1995). These studies revealed some seasonal changes in M, T_{rect} and skin temperatures, but could not demonstrate that wintertime cold acclimatisation occurred in a consistent manner.

It is possible that much of the modern cold acclimatisation is behavioural. Support for this hypothesis is found from a study where inhabitants of Northern Europe tended to protect their extremities more efficiently compared with residents from Southern Europe with a given fall in temperature (Donaldson *et al.* 2001). In this study the geographical differences in the use of hats, gloves and scarves were associated with cold-related mortality. Overall, mortality has been shown to increase to a greater extent with a given fall in temperatures in regions with warm winters, in households with low indoor heating, and among people wearing fewer clothes and being less active outdoors (The Eurowinter Group 1997). This observation would support behavioural adaptation to life in northern climates.

2.7 Acclimation to cold

2.7.1 Repeated exposures to cold air

An overview of the acclimation responses and their effects on thermal responses is given by Young (1996). The different acclimation protocols have employed various air temperatures and exposure durations and resulted in different cold acclimation patterns. Brief (2 h) exposures to cold air cause habituation of thermal sensations after only one or two repetitions (Leppäluoto *et al.* 2001). In general, short exposures (30 min to 1 h) to cold air result in shivering habituation (delayed onset of shivering, reduced VO_2 response) (Brück *et al.* 1976, Silami-Garcia & Haymes 1989, Hesslink *et al.* 1992), but in no marked changes in rectal or skin temperatures. Repeated cold exposures of longer duration (3 h to 14 days with cold exposures ranging from 5 to 15°C) result in hypothermic habituation, which involves both a reduced metabolic response towards cold exposure and lowered temperatures (Kreider *et al.* 1959, Davis 1961, Keatinge 1961, Mathew *et al.* 1981). Chronic, long-term exposure (several weeks of camping in tents with inadequate clothing and other type of protection) caused an increased M suggesting metabolic acclimation (Scholander *et al.* 1958b). However, this is one of the very few studies where metabolic acclimation has been demonstrated.

2.7.2 Repeated exposures to cold water

As heat loss in water is more pronounced than in air, the exposure temperatures and durations to cause acclimation responses are different from experiments performed in cold air (Young 1996). Repeated exposure of hands and fingers to cold water results in blunted vasoconstriction and higher peripheral skin temperatures. This phenomenon has been observed among specific occupational groups like British fish filleters (Nelms & Soper 1962), Gaspé fishermen (LeBlanc *et al.* 1960, LeBlanc 1962) and North Norwegian fishermen (Krog *et al.* 1960). Similar responses were also observed during cold-water acclimation trials (Eagan 1963, Lefteriotis *et al.* 1990).

Brief (10-90 min) repeated whole-body immersions into cold water (4-21°C) cause habituation responses (Lapp & Gee 1967, Radomski & Boutelier 1982, Muza *et al.* 1988, Budd *et al.* 1993, Stocks *et al.* 2001), for example, blunted metabolism (delayed onset and decreased intensity of shivering) and vasoconstriction. Although Jansky *et al.* (1996) observed less discomfort and delayed onset and reduced intensity of shivering, they also detected lowered skin temperatures, which would suggest insulative cold acclimation. Even three brief (60 min) immersions into cold water, where the temperature was reduced from 29 to 23°C, caused a reduced metabolic response and lowered T_{rect} (Marino *et al.* 1998). Golden & Tipton (1988) compared the effects of rest *vs.* exercise on the development of cold acclimation responses in water and found that the blunted responses observed during resting exposures were masked during exercising immersions. Similarly, Stocks *et al.* (2001) found that the blunted thermogenic response applied only to resting conditions and was abolished during light exercise in the cold water.

Whole-body immersion of longer durations (90 min to 3 h) into cold water (10-18°C) causes insulative or metabolic insulative acclimation (Young *et al.* 1986, Bittel 1987). Young *et al.* (1986) found lowered T_{rect} and T_{sk}, increased plasma NA concentrations and delayed onset of shivering after repeated immersion into cold water. Bittel (1987) detected similar thermal responses, but also an enhanced M after the acclimation, suggesting metabolic acclimation.

A study examining the importance of skin vs. core temperature in the development of cold acclimation due to repeated cold-water immersions (60 min exposures daily for 5 wks to 20°C) suggested that a decrease in skin temperature is sufficient for the increased vasoconstrictor response (O'Brien *et al.* 2000). However, a reduction in core temperature by ca. 0.8°C may be needed to enhance sympathetic activation during cold exposure.

2.8 Characteristics of cold exposure in the modern society

Modern humans have housing which separates them from the environment and reduces the cold strain. In many northern countries central heating has enabled high indoor temperatures in homes throughout the year. However, as an exception, there are still households in Europe, for example in Ireland, England and southern Europe, where indoor temperatures may be low enough in the winter to cause cold strain and different cold-related health hazards (The Eurowinter Group 1997, Ferriman 2001). For example, in Ireland, the measured bed and living room temperatures ranged between 9 to 12°C in winter (Middleton *et al.* 2000).

Another feature of life in modern societies is that the habitual cold exposure periods are probably short in indoor work. Previous studies assessing human activity patterns have demonstrated that people spend only 6-7% of their time outdoors, and the rest of the time indoors or in vehicles (Klepeis *et al.* 2001, Leech *et al.* 2002). For indoor workers, cold exposure is probably limited to commuting to work and leisure-time activities. An exception to this are people employed in the foodstuff industry who are subjected to cold exposure indoors for several hours per day.

Cold exposure may be substantial in certain outdoor occupations, lasting for several hours per day. In these conditions, thermal strain and adverse performance effects are likely to occur (Virokannas 1996). For example, Virokannas (1996) demonstrated that during cold days, in outdoor work of low physical activity, T_{sk} dropped in 41% of the cases below the recommended limit for performance degradation. Especially peripheral cooling is common in outdoor work. For example, in military training, during typical tasks of infantry and artillery training at 0 – -29°C, finger temperatures were at or below the limits of cold sensations (ca. 12ºC) for 20-69% of the total time (Rintamäki *et al.* 2004).

A factor reducing cold strain is modern cold protective clothing, enabling many activities to be carried out also under harsh environmental conditions. Due to adequate winter clothing, most often the only unprotected area of the body is the face, which is subjected to repeated daily cold exposure in winter. Facial cooling, aggravated by cold wind, may significantly affect the cardiorespiratory responses, for example increase BP markedly (Gavhed *et al.* 2000).

Finally, modern vehicles enable travelling or working in them without cold strain.

2.9 Gaps in the knowledge

It is not known to what degree people living in northern climates are exposed to cold at present. Studies examining time-activity patterns and physical activity have indicated that outdoor exposure may be relatively short. However, these studies were performed in mild/moderate climates and no special attention was paid to studying cold exposure *per se*; neither has it been identified which factors determine outdoor cold exposure. It could be assumed that differences in outdoor exposure can be observed between occupations. Also individual factors, such as age, gender, health and physical activity, could affect outdoor exposure in winter.

After identifying the degree of cold exposure, the next phase is to find out whether cold acclimatisation, in terms of thermal changes, occurs among urban residents of northern climates in winter. The information of urban cold acclimatisation is scanty, inconsistent and limited to mild/moderately cold climates.

Little attention has been given to examining the possible functional significance of human adaptation to cold climates. For example, the seasonal differences in cognitive performance are not well understood. These may arise from changes in temperature and the amount of light between winter and summer. It could be hypothesised that the increased prevalence of negative mood states in winter and possible changes in thermal responses and hormonal functions could cause impairment in cognition in winter.

Performing cognitive tasks requires sustained concentration and attention. The effects of non-hypothermic cold exposure on cognitive performance have yielded contradictory results, suggesting either a decline or improvement in performance. In this respect it would be important to study further cognitive performance during moderate cooling, the type of cold exposure that is likely to occur in everyday life. A special interest was to focus on determining the effects of moderate cold exposure on both simple and complex tasks as well as on the performance strategy (speed, accuracy, efficiency).

It is known that cold impairs physical performance. Especially the effects of cold exposure on dynamic and static tasks of moderate to high exercise intensity have been studied. However, many of the occupational or leisure-time activities are characterised by low physical activity, fine tuning of movements, adjustments, maintenance and tasks requiring attention or vigilance. These tasks involving low physical activity are most susceptible to cooling. One of the previously mentioned functions is postural control. An adequate postural control is especially important in winter when the environment is slippery and visibility may be limited. At present, it is not known whether body cooling affects whole-body postural control. It can be hypothesised that possible changes in sensory, neural and muscular functions may impair postural control in the cold.

Finally, it is known that repeated cold exposures cause habituation, which manifests as blunted physiological responses. It is possible that especially tasks requiring attention and concentration (e.g. cognition and postural control) could benefit from reductions in stress and discomfort related to cold habituation. It is also not known whether the performance strategy is altered due to repeated exposures to cold.

3 Aims of the study

One aim of this thesis was to examine to what extent people living in northern climate are exposed to cold during their daily activities, and to analyse factors affecting outdoor exposure at the population level. Another objective was to determine whether cold acclimatisation, in terms of seasonal changes in thermal responses, occurs among urban residents. It was also of interest to assess how seasonal changes in photoperiod and temperature affect cognitive performance in these residents. Finally, the aim was to determine how experimentally induced cold adaptation (acclimation), resulting in cold habituation responses, affects human performance in terms of cognitive functioning and postural control.

The specific aims of the study were as follows (the numbers in parenthesis refer to the original papers):

1. To analyse how ambient temperature, age, gender, occupation, place and type of residency, perceived health, physical activity and level of education affect outdoor occupational and leisure-time exposure in winter at the population level (I).
2. To determine whether seasonal acclimatisation to cold can be observed in thermal responses during moderate cold exposure, and examine what type of acclimatisation, if any, prevails in young urban residents. Specific interest was directed to studying the effects of season on thermal responses, thermal detection thresholds and thermal sensations (II).
3. To determine how moderate, non-hypothermic exposure to cold and darkness affects performance of simple and complex cognitive tasks and whether these effects vary by season (III).
4. To study how acute non-hypothermic cold exposure affects simple and complex cognitive tasks and whether repeated experimental cold exposures, causing cold habituation, affect cognitive performance. A specific interest was to assess possible changes in performance strategy over time due to repeated cold exposures. The study also aimed at producing a model of the effects of cold exposure and thermophysiological variables on cognitive performance (IV).
5. To study whether acute moderate cold exposure impairs whole-body postural control while standing. The other objective was to examine whether repeated exposure to cold, resulting in cold habituation, improves postural control (V).

4 Material and methods

4.1 Climatic conditions in Finland

Finland's climate is influenced by the country's geographical position between the 60th and 70th northern parallels in the Eurasian continent's coastal zone, which shows characteristics of both a maritime and a continental climate. Since Finland is located in the zone of prevailing westerlies where tropical and polar air masses meet, weather types can change quite rapidly, particularly in winter. The entire country of Finland belongs to the temperate coniferous-mixed forest zone with cold, wet winters, where the mean temperature of the warmest month is no lower than 10°C and that of the coldest month no higher than -3°C, and where the rainfall is, on average, moderate in all seasons. The length of the day varies markedly between the seasons. During winter the length of the day is 5 h (south) and less than 1 h in the north. In summer the day length is 19 h (south) and 24 h (north). Winter is the longest season in Finland. If defined as the number of days when the mean daily temperature is below 0°C, winter lasts for about 100 days in southwestern Finland and 200 days in Lapland. The coldest days of winter occur at the end of January–early February. The lowest temperatures in winter are from -45°C to -50°C in Lapland and eastern Finland; from -35°C to -45°C elsewhere; and -25°C to -35°C in the islands and coastal regions (Finnish Meteorological Institute, Climate services).

In 2001, while collecting data for Study II, the average monthly temperatures in Oulu ranged from -4 to -12°C (winter measurements) and from 11 to 14°C (summer measurements). The length of daylight ranged from 6.1 to 9.1 h (winter) and from 10.6 to 16.7 h (summer). When assessing the amount of outdoor cold exposure (Study I) in 2002 (January-March), the January mean daytime temperatures ranged from -2.6°C (Helsinki in southern Finland) to -12.1°C (Lapland in northern Finland) and in April from 7.0°C (Helsinki) to 3.4°C (Lapland). The measurements for studies IV and V were conducted in August-November 2003. During this period the mean monthly temperatures in Oulu ranged between 14.3°C (August) and -0.5°C (November).

4.2 Subjects

4.2.1 FINRISK population study assessing cold exposure (I)

In 2002 the national FINRISK study was carried out in six areas of Finland. The data were collected between January and April 2002. A random sample of 13,437 people was drawn from the national population register of each area (Helsinki/Vantaa, Turku/Loimaa, Kuopio, Oulu, North Karelia and Lapland). The sample included people aged between 25 and 64 years stratified by sex and 10-year age groups, each stratum containing 250 subjects. In addition, 500 subjects aged 65-74 years were included in Helsinki/Vantaa, Lapland and North Karelia. The stratification of the samples followed the WHO MONICA study protocol (1988) and is described in more detail by Vartiainen *et al.* (2000). The FINRISK study is a national survey focusing mainly on cardiovascular risk factors and their surveillance. The cold exposure sub study consisted of a 76% random sample of the FINRISK survey population (n=10,256), and a total of 6,591 persons (64%) participated. The size of the sample was determined by the fact that several sub-studies were included in the main FINRISK study, which allowed examining only a certain portion of the entire study population. The study areas were influenced by historical reasons related to the FINRISK study design, but allowed us at the same time to examine possible north-south and urban-rural differences in cold exposure. In the cold sub-study the participation rates varied depending on the study area, age and gender, ranging from 64% to 73% among men of different ages, and from 48% to 69% among women.

4.2.2 Experimental studies (II-V)

The laboratory studies were conducted in Oulu (65°N, 25°E) in Northern Finland. Healthy young urban men living in Oulu volunteered in the laboratory studies (II-V). The experimental protocols were approved in advance by the ethics committee of the University of Oulu and Northern Ostrobothnia Hospital District. The subjects were students/indoor workers and non-smokers. They were recruited to the experiments by announcements. All subjects underwent a medical examination, and those being hypersensitive to cold (e.g. cardiovascular or respiratory symptoms or other abnormalities) were excluded from the studies. In Study III a psychological screening was carried out to exclude subjects with SAD or possible other mental disorders. The subjects selected to the studies were reimbursed for the time spent with the studies, as well as for the incurred expenses. Before the experiments the study protocols, risks and inconvenience related to the tests were described to them, and a written consent was obtained. For assessing fitness a maximal VO_2 test was performed with a bicycle ergometer (IV-V). For determining body fat percent, skin fold thickness was measured from biceps, triceps, subscapularis and suprailiaca (Durnin & Rahaman 1967). The physical characteristics of the subjects participating in the laboratory trials are described in Table 1.

Table 1. Physical characteristics of the subjects in the laboratory studies. Values are represented as means±SD.

Study II-III	Age (yr)	Height (cm)	Weight (kg)	BMI	Body fat %	VO_{2max}*
Summer (n=8)	24.3 ± 0.4	180.6 ± 1.6	76.8 ± 3.0	23.5 ± 0.7	19.0 ± 0.9	-
Winter (n=7)	24.3 ± 0.7	178.9 ± 1.3	69.6 ± 1.9	21.8 ± 0.8	16.7 ± 1.0	-
Study IV-V (n=10)	22.5±1.6	180.8±7.2	72.4±7.3	22.3±1.6	17.1±1.9	53.1±6.1

*$ml \cdot min^{-1} \cdot kg^{-1}$

4.3 Study designs

4.3.1 FINRISK population study assessing cold exposure (I)

A questionnaire assessing cold exposure duration, comfort, clothing, performance, symptoms of diseases and diagnosed diseases was mailed to the participants before attending a medical examination. For determining the duration and type of cold exposure, the following questions were asked in the questionnaire: 1) to what extent (hours per week) have you been exposed to cold during the past winter (below 10°C) while commuting to work (either walking or travelling in an open vehicle)? 2) To what extent (hours per week) have you been exposed to cold at work (exposure to cold air without a wind shelter or in unheated workspaces) during the past winter? 3) How many hours per week have you been exposed to cold during your leisure time (exposed to cold air and/or wind)? The independent variables analysed in association with cold exposure were: age, occupation, self-rated health, physical activity, level of education, area of residence. A detailed description of the classification of these variables is described in Study I. The study also assessed whether geographical variations in winter temperatures affect self-reported outdoor exposure. For this purpose, temperature data from 31 meteorological stations were included in the analyses. The mean daytime temperatures (active hours) of January (the coldest month) were used for the analyses. The temperature data from the weather stations were linked to the area of residence of each respondent. The numbers of weather stations used in the analyses in each area were as follows: Northern Karelia 3, Kuopio 4, Turku/Loimaa 3, Oulu 9, Lapland 10 and Helsinki 2.

4.3.2 Seasonal effects on thermal responses and cognition (II, III)

For examining seasonal effects on thermoregulation and cognitive performance (II-III) seven subjects were measured in the laboratory during the winter (January-March 2001) and eight in the summer (August-September 2001). The initial purpose was to compare the same individuals in different seasons. However, only three subjects were able to participate in the measurements in both seasons. Hence, additional subjects were recruited for the summer measurements. The climatic conditions during the experiments are described in chapter 4.1.

The preparation of the subjects started at 12:00 and the measurements began at 14:00. During the experiment, the subjects were lightly dressed in a Finnish military underwear ensemble consisting of short-legged underpants, a t-shirt, a long-sleeved undershirt, long-legged underpants, socks and athletic shoes. The clothing insulation value (clo) of this ensemble was approximately 0.7 clo (ISO 9920).

The subjects entered the climatic chamber sized 26 m^2, where the temperature was either 22.0 ± 0.3°C (mean±SD), or 10.0 ± 0.3°C. The relative humidity of the chamber was 50 ± 3% and the air velocity was less than 0.2 $m \cdot s^{-1}$. The level of light was adjusted either to 500 lx (standard office room) or 0.5 lx (deep twilight). The duration of each exposure was 24 h. The order of the exposures was randomised and the time between each exposure was at least one week. All measuring equipment was located inside the climatic room.

During the 24-h exposure, the subjects were provided lunch (two times), dinner and breakfast (total energy content ca. 2,700 kcal). The same meals were provided to all participants. The subjects were allowed to drink *ad libitum*. Caffeine was prohibited during the exposure. The subjects left the climatic room only when going to the toilet. When not performing any tests, the subjects were resting. The subjects slept in sleeping bags between 23:00 and 07:00.

4.3.3 Repeated cold exposures study (IV, V)

During the experiment the subjects were lightly clad in shorts, socks and athletic shoes (ca. 0.1 clo). They were exposed on ten consecutive days to control (25.0±0.3°C) and cold (10.0±0.3°C) conditions during which different sets of performance tests were performed. The duration of the stay at control conditions was 90 min. Immediately after this the same subjects where exposed to cold for 120 min. The experiments were conducted from 10:00 to 15:00, and two subjects were measured each day. The performance tests (cognition, postural control) were conducted at the same time of the day for each subject. Cognitive performance (IV) was assessed each day under control conditions after 90 min and in cold after 100 min of exposure. For determining postural control (V) the tests were performed under control conditions on days 1, 5 and 10 and in the cold each day (Days 1-10) after 90 min of exposure.

4.4 Measurements

4.4.1 Temperatures (II-V)

Skin temperatures were measured using either YSI (YSI 409b and 427, Yellow Springs Instrument Co., Yellow Springs, USA) (II-III) or Digi Key thermistors (NTC DC 95, type 2252OHM Digi Key, USA (IV-V). The thermistors were calibrated in a temperature bath prior to use. The measured sites (10) were: forehead, scapula, chest, abdomen, upper arm, lower arm, back of the hand, anterior thigh, calf and dorsal side of the foot. Mean skin temperature (T_{sk}) was calculated as an area-weighted average from these 10 sites (Hardy & DuBois 1938).

Rectal temperature (T_{rect}) was measured 10 cm beyond the anal sphincter with an YSI401 probe (Yellow Springs Instrument Co., Yellow Springs, USA).

Skin and rectal temperature were recorded at 1-min intervals with dataloggers. Two types of loggers were used (Squirrel 1200, Grant, UK and SmartReader Plus8, ACR Systems, Canada).

Calculations:

- Mean skin temperature (T_{sk}) was calculated as an area-weighted average from 10 sites of the skin according to the following formula: $0.07 \cdot (T_{forehead}) + 0.35 \cdot \text{mean}(T_{chest}, T_{scapula}, T_{abdomen}) + 0.14 \cdot \text{mean}(T_{upper\ arm}, T_{lower\ arm}) + 0.05 \cdot (T_{dorsal\ hand}) + 0.19 \cdot (T_{thigh}), + 0.13 \cdot (T_{calf}) + 0.07 \cdot (T_{dorsal\ side\ of\ foot})$ (Hardy & DuBois 1938).
- Mean body temperature (T_b) was calculated by the equation: $T_b = 0.65 \cdot T_{rect} + 0.35 \cdot T_{sk}$.
- Body heat content (Q) was calculated as follows: specific heat of tissues (c) (3.48 $kJ \cdot kg^{-1} \cdot °C^{-1}$)$\cdot$ body mass (kg) $\cdot$ T_b (Bittel, 1987). Heat storage (S) (i.e. the rate of decrease in heat content) was calculated by subtracting body heat content in cold from that measured in a warm environment.

4.4.2 VO_2 measurements (II, IV, V)

In Study II, oxygen consumption (VO_2) was measured four times at 3.5, 7, 19.5 and 23 h from the beginning of the exposure. In Study V, VO_2 was assessed after being exposed to cold for 60 min. The subjects were sitting during the measurements. A portable analyser (Cortex Biophysik, MetaMax 3B, Germany) employing a breath-by-breath system was used. The duration of each measurement was 10 minutes. The average from the last five minutes, where VO_2 was stabilised, was used for the analyses.

4.4.3 Finger blood flow (II)

Finger skin blood flow (Q_f) was determined at 3.5, 7, 19.5 and 23.00 h after the beginning of the exposure using Laser Doppler flowmetry (Oxford Optronics, Oxford Array, UK). Laser Doppler probes were placed on the dorsal and palmar side of the middle finger. The probe was attached with adhesive material to the middle phalanx of the finger. The exact relocation of the probes for each consecutive test was ensured by marking their place. Blood flow was measured for two minutes. For the analysis, a 10-s stable portion of the data was selected.

4.4.4 Heart rate and blood pressure (IV)

In Study IV, heart rate (HR) was measured continuously using a Polar Sport Tester monitoring device (Polar Electro Inc., Finland). Systolic (SBP) and diastolic (DBP) blood pressure was measured from sitting subjects immediately after completing the cognitive tests using an ambulatory blood pressure monitoring device (Meditech ABPM-04, Meditech Ltd., Hungary).

4.4.5 Thermal sensitivity (II)

Thermal sensory thresholds were assessed by quantitative sensory testing at 3, 6.5, 19 and 22.5 h after the beginning of the exposure using a SenseLab-Thermotest Modular Sensory Analyzer (SOMEDIC scales, Sweden), and the method of levels algorithm were used (Yarnitsky 1997). The subjects were seated and one arm was placed in a relaxed position on a table. The subject placed the thermode (stimulator) (2.5 x 5.0 cm) on their right palm (thenar eminence). The initial temperature (baseline adaptation temperature) of the thermode was 32°C and, if necessary, it was adjusted to correspond to the individual thermoneutral temperature. Following the recording of the baseline temperature, both ascending and descending temperature stimuli were applied five times at mixed (4-6 s) intervals. A 1°C/s temperature change rate was used. The subjects pressed a button when they sensed the stimulus being ”colder” at their cold detection threshold (CDT), or ”warmer” at their warm detection threshold (WDT) compared with the baseline temperature. The average sensory threshold temperature values were calculated from five repetitions.

4.4.6 Thermal sensations and comfort (II-V)

Thermal perception for the whole body, trunk, hands and feet was assessed using subjective judgment scales (ISO 10551). The thermal sensation scales ranged from 4 (extremely hot) to -4 (extremely cold). Thermal comfort was assessed using a 6-degree scale ranging from 0 (comfortable) to 5 (extremely uncomfortable).

4.4.7 Shivering, EMG (II, V)

Muscle tonus was assessed by measuring surface electromyographic (EMG) activity (models ME3000P8 and ME6000, Mega Electronics, Kuopio, Finland) from *M. pectoralis.* The electrodes were placed above the belly of the muscle. The distance between the recording contacts was 2 cm. Ground electrodes were attached above on inactive tissues. Raw EMG signal (sampling rate 250 Hz) was recorded continuously throughout the exposure. The signal was amplified and the signal band between 8-500 Hz was full-wave rectified and averaged (aEMG) with a 40 ms time constant. Butterworth filtering was used in the 8-500 Hz measuring band. The common mode rejection rate of the amplifier was 110 dB.

In Study II, EMG was measured for 2 min on four occasions during the 24-h exposure (at 17:30, 21:00, 09:30, 13:00) and in Study V while assessing postural sway (after 90 min of cold exposure).

4.4.8 Cognitive performance (III, IV)

Cognitive performance was assessed using test batteries consisting of both complex and simple cognitive tasks. Prior to the tests the subjects were familiarised with the test batteries and were allowed to rehearse the tasks one time. In Study III, a battery of computerised cognitive performance tasks adapted from the Naval Medical Research Institute (NMRI) Performance Assessment Battery (PAB) was administered (Shrot & Thomas 1988). The battery consisted of the following tasks: matching-to-sample, simple reaction time, addition/subtraction, grammatical reasoning and repeated acquisition of response sequences. The tests are described in more detail in Study III. For each of the tasks, accuracy (% correct responses) and response times (ms) were measured.

In Study IV, the Automated Neuropsychological Assessment Metric (Reeves *et al.* 1995) and a modification for Isolated and Confined Environments (ANAM-ICE) version was administered. Unlike most other computerised batteries, the ANAM uses accuracy (% correct responses) and response times (ms) to calculate the throughput (efficiency). The efficiency measure and the ANAM battery have proven to be a valid tool and sensitive to changes in neurocognitive functioning in several clinical studies. Furthermore, it is especially usable in studies requiring repeated testing, and has shown high test-retest reliability (Kabat *et al.* 2001, Levinson *et al.* 2005). In our study, the program was translated into Finnish. The test battery consisted of the following tasks: code substitution and code substitution delayed, logical reasoning, matching-to-sample, continuous performance, simple reaction time and Sternberg memory search. For each of the tasks, accuracy (% correct responses), response times (ms) and efficiency (%) were measured. A more detailed description of these tasks is provided in Study IV. Table 2 summarises which function of cognitive performance the different tests assess.

Table 2. Cognitive performance tasks administered in studies III and IV.

Cognitive task	Study	Assessed cognitive function
Matching-sample	III, IV	Spatial and short-term or working memory
Simple reaction time	III, IV	Simple visuomotor mental flexibility
Serial addition/subtraction	III	Sustained attention
Grammatical reasoning	III	Logical reasoning
Repeated acquisition	III	Learning capability and short-term memory
Code substitution and code substitution delayed	IV	Sustained attention and concentration, verbal learning, and numeric and symbolic facility
Logical reasoning	IV	Abstract reasoning and verbal syntax
Continuous performance	IV	Encoding, storage and use of working memory
Sternberg's memory search	IV	Encoding, categorisation, response selection, execution, and visual and short-term memory

4.4.9 Postural control (V)

A novel inclinometer-based method was used in this study (Body Sway Measurement System, Crea Research, Oulu, Finland). The method measures the absolute movements of the body (both momentary and cumulative values). The method has proven an accurate and repeatable method and useful in clinical applications (Viitasalo *et al.* 2002, Korpelainen *et al.* 2005). The device consisted of a belt fastened firmly at the level of the sacrum, an inflexible measuring rod, an inclinometric module, a special joint structure located on the ground, a power unit and a PC. The measuring rod transmitted movements of the body to the detecting inclinometric module. The measurement resolution of this module was less than 0.5 mm and the high cut-off frequency was 25 Hz. The height of the measuring rod was adjusted according to the estimated centre of mass (0.55 x height).

Prior to the experiments the subjects were familiarised with the equipment and the measurement protocol. During the sway measurements the subjects stood at attention with their feet together and arms alongside the body, keeping their eyes successively open (EO) or closed (EC). In the EO test the subjects were asked to look straight ahead at a fixation point on the facing wall 4 m in front of them. The tests were performed under quiet and well-lit circumstances and repeated once. The duration of each measurement was 1 min. The recorded sway parameters were: the total path length of postural movements (at the level of 0.55 x subject's height), maximum deflection for x (side-to-side) and y (forward-backward) sway (cm), velocity ($cm \cdot sec^{-1}$) and total sway area (cm^2).

4.5 Statistical analyses

In Study I, medians, lower (25th percentile, IQ1) and upper (75th percentile, IQ3) quartiles for occupational and leisure-time cold exposure were calculated. A robust analysis of covariance (ANCOVA) was used to analyse their associations with the explanatory factors (see Study I for a more detailed description). The independent variables entered into the model were: age, area of residence, type of area, occupation, self-rated health, physical activity, level of education (categorical variables) and mean daytime temperature for January (continuous variable).

In Study (II) means of skin and rectal temperatures within one exposure were compared by the repeated measures ANOVA (within-subject factor: test time), followed by Newman-Keuls post-hoc tests. The effect of temperature (22°C vs. 10°C) was tested by paired samples t-tests. Seasonal differences between the two study populations were compared by independent samples t-tests. A linear regression analysis was used when analysing the effects of season, exposure, and thermoregulatory parameters on thermal sensitivity. Median values were calculated from thermal sensations. The relationship between thermal sensations, thermal sensitivity and thermoregulation were analysed by Spearman correlation tests. Separate group means were compared by the Wilcoxon Signed-Rank (more than two groups), Kendall's W or Mann-Whitney's U-test (two populations) (II-V).

In studies IV and V, the effect of exposure period on thermal parameters was tested by the repeated measures ANOVA (within-subject factor: day of exposure 1-10). Separate days were compared by simple contrasts (equivalent to paired samples t-tests). To control for multiple comparisons, the observed p-values were adjusted using the Bonferroni-method (IV). The effect of temperature (25°C versus 10°C) was tested by paired samples t-test.

In Study IV, cognitive performance measures (accuracy, response time, efficiency) were compared by temperature exposure (25°C versus 10°C) and by day of testing using the paired samples t-tests. A repeated measures ANOVA was conducted to determine if cognitive performance changed over the 10-d period. Associations between cognitive performance and physiological measures were analysed by Spearman's correlation coefficients. A pooled time series method (Ward & Leigh 1993) was used for multivariate analyses of the independent effects of test order, exposure to cold and physiological measures of thermoregulation on test accuracy, efficiency and response time of all of the cognitive tasks combined. A least squares dummy variable regression model and fixed effects was used (see paper IV for a more detailed description). Significance was set at $p < 0.05$ in all of the studies.

5 Results

5.1 Population cold exposure to cold in winter

The self-reported total cold exposure time was 7 h/week, accounting for 4% of the total time. For all respondents the weekly median (Md) cold exposure time at work was 0.3 h per week (IQ1, IQ3, 0-5 h, n=3,047), and 2 h (IQ1, IQ3, 0-11 h, n=1,598) for men and 0 h (IQ1, IQ3, 0-1 h, n=1,449) for women. Among all respondents (n=6,011), the median weekly leisure-time cold exposure was 5 h (IQ1, IQ3, 3-8 h). On the average, men were exposed to cold one h more per week (Md 5 h, IQ1, IQ3, 3-10 h, n=2,747) during their leisure time than women (Md 4 h, IQ1, IQ3, 2.5-7 h, n=3,264). For all respondents (n=3,510) the median exposure time while commuting to work was 1 h per week (IQ1, IQ3, 0-3 h). While travelling to work, men were less exposed (Md 1 h, IQ1, IQ3, 0-2.5 h, n=1,556) than women (Md 1.5 h, IQ1, IQ3, 0-3 h, n=1,954). In general, men were more exposed to cold both at work and during leisure time than women (Fig 2, Study I, Tables 1 and 3).

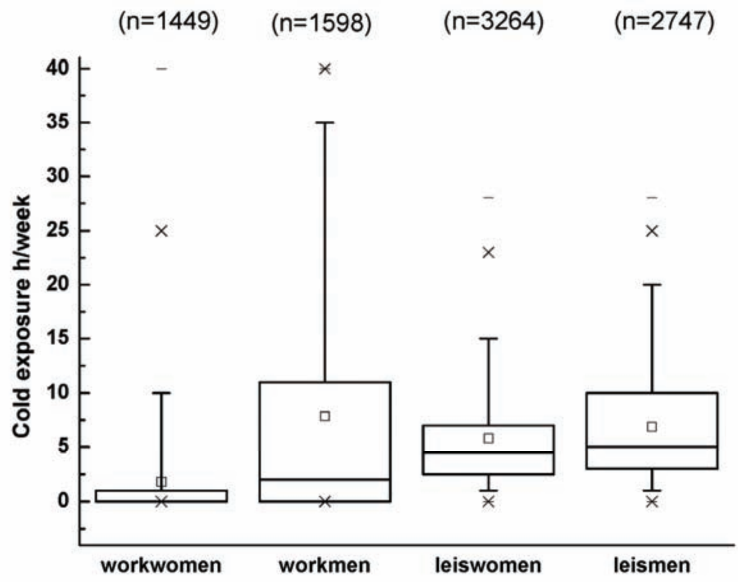

Fig. 2. Self-reported cold exposure at work (workwomen, workmen) and during leisure time (leiswomen, leismen) in men and women. Boxplot symbols: X=1% and 99% percentiles, □=mean, ━ =min and max-values.

Factors affecting cold exposure. Among men, the duration of cold exposure at work was 8.5 h longer per week (95% CI 7.6 to 9.3) among those employed in agriculture than those employed in office work. A corresponding excess of 1.1 h per week (95% CI 0.5 to 1.6) was also observed among men working in industry or related occupations. When analysing the differences in cold exposure between the study areas, cold exposure was 4.6 h per week longer for men living in the archipelago (95% CI 2.1 to 7.1) compared with those living in urban areas. The duration of cold exposure at work increased by 1.0 h per week from the youngest age group to those aged 55-64 yrs. (95% CI 0.2 to 1.7). A lesser amount of education (elementary school) was associated with 2.3 h longer (95% CI 1.5 to 3.0) cold exposure at work compared with an academic education. Self-rated health, physical activity, study area and ambient temperature did not affect the reported amount of cold exposure at work in men. No significant differences were observed in the factors explaining occupational cold exposure for women.

While commuting to work the weekly cold exposure time tended to increase slightly by age in women and was 0.3-0.4 h longer (95% CI 0.1 to 0.7) in women aged 45-64 years compared with the youngest age group. Men and women living in the Helsinki study area spent 0.4 to 1.1 h more time commuting to work compared with the other areas (other areas 95% CI 0 to -2.3 h). Similarly, people living in rural or remote areas spent 0.4-0.8 less time (95% CI for men and women 0.1 to 1.1 h) exposed to cold while commuting to work than in urban areas. Male and female students were more exposed to cold (0.8-0.9 h) (men 95% CI 0.4 to 1.2, women 95% CI 0.5 to 1.3) when travelling to work compared with office workers. Furthermore, those respondents who were exercising to an average amount were more (0.2-0.4 h) (men 95% CI 0.0 to 0.7, women 95% CI 0.0 to 0.5) exposed to cold than those having no exercise at all, while perceived health had no effect on weekly exposure times.

During leisure time, ageing was associated with 0.4-0.6 h (95% CI 0.0 to -1.2) less cold exposure among women aged 45-74 years and 0.8 h (95% CI 0.0 to -1.7) in men aged 65-74 compared with the youngest age group (Study I, Table 3). Male pensioners and unemployed men showed 2-3 h longer exposure times per week (pensioners 95% CI 1.6 to 3.0, unemployed 95% CI 2.0 to 3.6) during their leisure time than men engaged in office work. Also men practising at least some exercise were 2.5-2.7 h more exposed to cold during their leisure time (95% CI 1.3 to 4.0). Those men reporting at least average health were 2.3-2.4 h more exposed to cold (95% CI 0.0 to 4.7). Men having a vocational or college education were also 0.7-0.9 h (95% CI 0.0 to 1.8) more exposed to cold per week compared with those with academic education. Area or type of area of residence or ambient temperature did not affect the weekly exposure time in men. Among women, pensioners, unemployed, housewives and those who were physically active showed 1.5-2.7 h longer exposure times per week compared with indoor workers or physically inactive women. Area, type of area, perceived health, education and temperature did not explain cold exposure during the leisure time in women (Study I, Table 3).

5.2 Thermal responses related to cold acclimatisation and acclimation

5.2.1 Seasonal changes in thermal responses (II)

When exposed to cold (10°C) for 24 h, T_{sk} decreased to about 28-29°C (Study II, Fig. 1), and the average decrease of the body heat content (S) was 344 kJ (winter) and 362 kJ (summer). T_{sk} decreased 0.7°C more in the winter than in summer but remained at a significantly higher level ($p<0.05$). Furthermore, finger temperatures (T_f) decreased on average more in winter (11.8°C) ($p<0.05$) compared with summer (8.4°C), indicating enhanced vasoconstriction in hands. This is supported by the observation that blood flow in fingers (Q_f) was also significantly lower in winter (94% decrease in cold, $p<0.05$) compared with summer (71% decrease in cold). When examining the skin temperature of the individual sites at 22°C, 11 out of 12 sites were warmer in the winter. However, at 10°C, only 4 out of 12 sites, located mainly on the trunk (chest, stomach, scapula, calf), were warmer in winter compared with summer. There were no seasonal differences in T_{rect} during the daytime cold exposure. Seasonal differences in nocturnal values of T_{rect} were observed only at 22°C, where it was significantly lower in winter ($p<0.05$) compared with summer at specific time points (04:00 and 06:00). M increased more in winter (14%) compared with summer (7%) ($p<0.05$).

When assessing thermal detection thresholds, a more considerable drop in temperature of the thermode was required in winter (4.3°C) than in summer, (2.9°C) ($p<0.05$) before the subjects sensed it as cold (Study II, Table 3). This change in CDT was associated with the lower skin temperatures measured in hands and fingers in the winter. There were no seasonal differences in the WDT. According to the reported thermal sensations (general and local), the subjects were likely to report feeling slightly colder (general and local thermal sensation) ($p<0.05$) in the winter than in the summer (Study II, Table 4).

5.2.2 Thermal responses due to cold acclimation (IV, V)

Repeated exposure to cold for 10 days resulted in different changes in thermal responses (Fig. 3, unpublished results). On average, the cold exposure (2 h at 10°C) decreased T_{sk} by 6-6.4°C compared with 25ºC ($p<0.05$-0.01), and the decrease of the body heat content ranged between 566-630 kJ during the 10-d exposure. T_{rect} decreased on average 0.3-0.4°C ($p<0.05$) and T_f by 15.3-16.1°C ($p<0.001$) after being cold-exposed for 120 min.

When examining the changes in thermal responses over the 10-d period T_{sk} was significantly higher on Day 10 compared with Day 1 after 30 min (0.8°C higher, $p<0.05$) and 120 min of cold exposure (0.6°C higher, $p<0.05$). Similarly, T_{fing} were higher on Day 10 compared with Day 1 after 30 min (2.0°C higher, NS) and 120 min of cold exposure (1.9°C higher, NS). Cold increased M on average by 13-18%. VO_2 was significantly lower in the cold on Day 10 compared with Day 1 ($p<0.05$). Cold increased serum NA concentrations on average by 48%, but the rise was significantly less ($p<0.05$) on Day 10 compared with Day 1. Adrenaline (A) concentrations remained unchanged by cold and during the 10-d period. Less intense cold sensations were experienced by the end of the acclimation period (Day 10) compared with Day 1. The general thermal sensations after 5 min of cold exposure were “cool” (Day 1) and “slightly cool” (Day 10). The sensations after 120 min were “cold” (Day 1) and “cool” (Day 10).

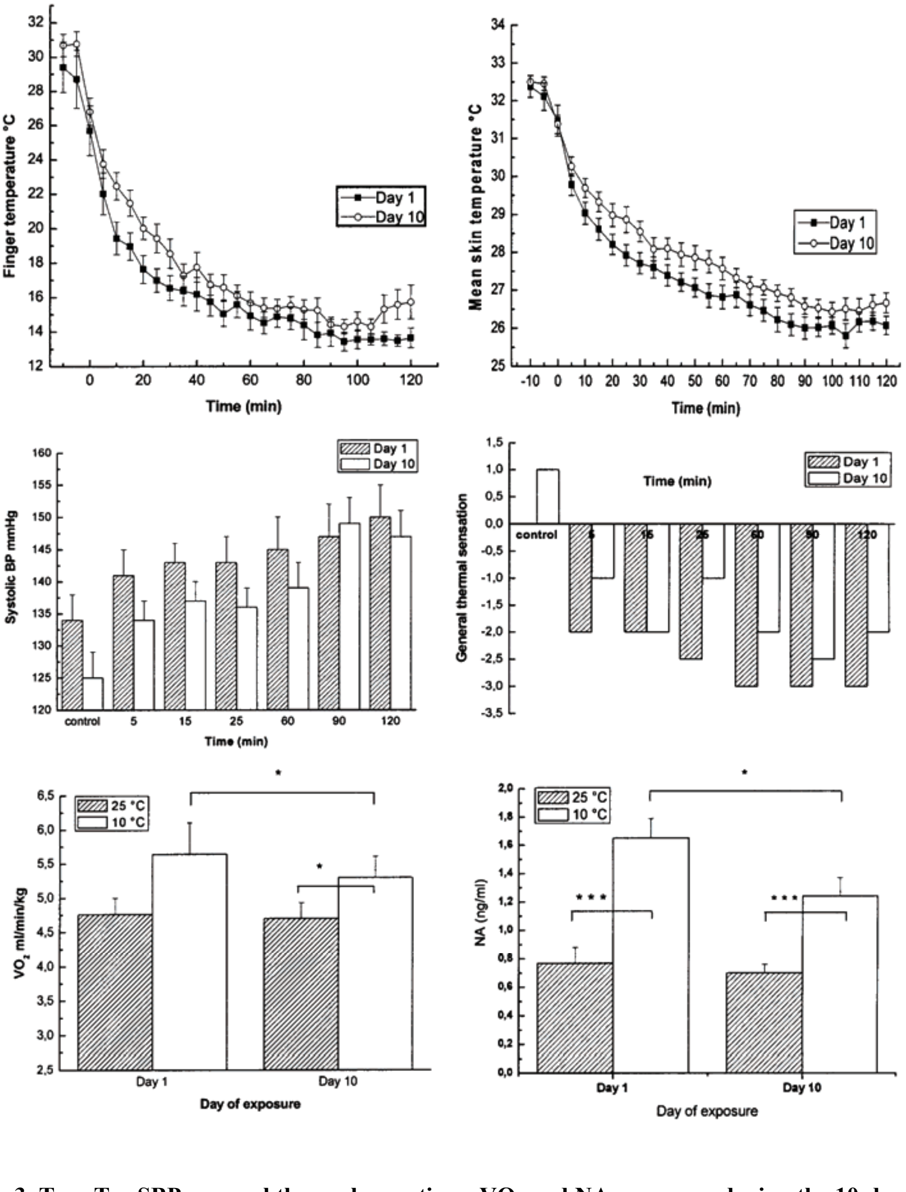

Fig. 3. T_{fing}, T_{sk}, SBP, general thermal sensations, VO_2 and NA responses during the 10-d cold acclimation period (mean±SE). General thermal sensation: 1=slightly warm, 0=neutral, -1=slightly cool, -2=cool, -3=cold, -4=very cold.

5.3 Effects of cold acclimatisation and acclimation on cognitive performance

5.3.1 Effects of season, cold and light on cognition (III)

A 24-h exposure to both cold and dim light was associated with increased accuracy on three complex cognitive tasks (grammatical reasoning, matching to sample and repeated acquisition) and a decreased accuracy on two simple tasks (addition/subtraction and simple reaction time) ($p<0.01$-0.001, Study III, Table 3). All cognitive tasks were performed faster in the cold and dim conditions, as judged by the shorter RTs on both simple and complex cognitive tasks (Study III, Table 1). The independent effect of cold resulted in improved accuracy in the grammatical reasoning and repeated acquisition task ($p<0.01$-0.001, Table 1) and decreased accuracy in the simple reaction time task ($p<0.001$). Response times were significantly shorter in the cold in 4 tasks (Table 1). A change in the level of light alone did not affect accuracy, but it caused a reduction in RTs in the grammatical reasoning ($p<0.05$) and matching to sample ($p<0.05$) tasks.

Seasonal differences were observed in only two tasks, where the accuracy of the addition subtraction task was higher in summer than winter ($p<0.05$). On the other hand, the repeated acquisition task was performed more accurately in winter than in summer ($p<0.01$) (Study III, Table 2). However, when season was examined as an independent predictor no effects on accuracy were observed, but RTs were longer in the summer in the grammatical reasoning ($p<0.05$) and simple reaction time tasks ($p<0.001$) (Table 3).

T_{sk} was inversely associated with accuracy on the grammatical reasoning ($r=-0.2$, $p<0.01$), matching to sample ($r=-0.15$, $p<0.05$) and repeated acquisition tasks ($r=-0.19$, $p<0.05$). Furthermore, a decrease in T_{sk} was associated with shorter RTs in all cognitive tasks ($r=0.18$-0.38, $p<0.05$-0.001). Cognitive performance was unrelated to changes in T_{rect}. An increase in cold-related discomfort was positively associated with response times on the grammatical reasoning task ($r=0.15$, $p<0.05$). Table 3 (Study III, Table 3) summarises the effects of time of day, test sequence, condition (temperature, light) and season on the different cognitive tasks.

Table 3. The independent effects of test time, test sequence (no. of tests performed), condition (warm, cold, bright and dim light) and season (winter, summer) on the performance accuracy and response times of different cognitive tasks (modified from Study III, Table 3).

Factor	Grammatical Reasoning	Matching to Sample	Addition/ Subtraction	Simple Reaction time	Repeated Acquisition
Accuracy					
Time of day	Higher accuracy	Higher accuracy	No effect	No effect	Higher accuracy
Test sequence	No effect	No effect	No effect	No effect	No effect
Condition[a]	Higher accuracy	Higher accuracy	Lower accuracy	Lower accuracy	Higher accuracy
Season[b]	No effect	No effect	No effect	No effect	No effect
Response time					
Time of day	Shorter RT	No effect	Shorter RT	Shorter RT	No effect
Test sequence	No effect	No effect	No effect	No effect	No effect
Condition[a]	Shorter RT	Shorter RT	Shorter RT	Shorter RT	Shorter RT
Season[b]	Longer RT in summer	No effect	No effect	Longer RT in summer	No effect

a) condition 1=22°C, 2=10°C bright light, 3= 10°C dim light, b) 1=winter, 2=summer.

5.3.2 Effects of cold acclimation on cognition (IV)

When all the administered cognitive tasks were combined in a regression model, cold exposure was associated with improved accuracy, but at the same time longer RTs, leading to reduced efficiency. However, when examining the effects of cold on individual tests both positive (reduced response time), negative (reduced accuracy and longer RTs) and mixed (increased accuracy but longer response time, or reduced accuracy but also shorter response time) effects were observed (Study IV, Tables 2 and 5). The 10-d exposure period resulted in significantly improved efficiency and shorter RTs over time in both warm and cold conditions. At 25°C efficiency improved in five and at 10ºC in four tasks. RTs were significantly shorter over time in one task (continuous performance) at 25ºC and six tasks at 10ºC. Accuracy improved over the 10-d period in the cold in four tasks (code substitution, code substitution delayed, logical reasoning, Sternberg 6) ($p<0.05$-0.01). With a few exceptions, there were no marked differences in the magnitude of changes occurring during the 10-d period between warm and cold conditions.

Of the thermal parameters, a reduction in T_{rect} was associated with shorter RTs in six out of seven tasks ($r=0.24$-0.32, $p<0.001$) and improved efficiency in all seven tasks ($r=0.20$-0.30, $p<0.01$-0.001) (Study IV, Table 4). Decreased T_{sk} and T_f were associated with longer RTs ($r=-0.35$- -0.41, $p<0.01$-0.001) and reduced efficiency ($r=0.22$-0.25, $p<0.01$-0.001) in the simple reaction time task. In the regression model a low T_{rect} predicted an increased efficiency ($p<0.001$) and shorter RTs ($p<0.001$) in the Simple RT task (Study IV, Table 5). Furthermore, an increased DBP predicted reduced efficiency ($p<0.001$) and increased RT ($p<0.01$), and an increased HR predicted improved efficiency ($p<0.01$) and reduced RTs ($p<0.05$) on this task as well. Repetition of the cognitive tests (test order) improved efficiency ($p<0.001$) and shortened RTs in complex cognitive tasks ($p<0.001$). Exposure to cold was a significant independent predictor of increased accuracy ($p<0.01$) but longer RTs ($p<0.001$) and decreased efficiency ($p<0.001$). In complex tasks a lowered T_{rect} predicted improved efficiency ($p<0.001$) and shorter RTs ($p<0.001$). Furthermore, an increased DBP and lowered HR predicted decreased accuracy ($p<0.001$) and shorter RTs ($p<0.05$). Thermal sensation of cold in the hands was a significant independent predictor of decreased accuracy ($p<0.05$) and shorter response time ($p<0.05$) (Table 4).

Table 4. Results of regression analysis of cognitive performance accuracy, efficiency and RT in simple and complex cognitive tasks (Study IV, Table 5). The Simple Reaction time-task has 100% accuracy. Hence, accuracy of this task was not included in the regression model.

Parameter	Accuracy	Efficiency	Response time (RT)
Simple task*			
Number of tests	-	No effect	No effect
Cold exposure	-	No effect	No effect
Cold sensations in hands	-	No effect	No effect
Decrease in T_{rect}	-	Increased efficiency	Shorter RT
Increase in DBP	-	Lower efficiency	Longer RT
Lowering of HR	-	Lower efficiency	Longer RT
Increase in O_2 intake	-	No effect	No effect
Complex task**			
Number of tests	No effect	Increased efficiency	Shorter RT
Cold exposure	Higher accuracy	Lower efficiency	Longer RT
Cold sensations in hands	Lower accuracy	No effect	Shorter RT
Decrease in T_{rect}	No effect	Increased efficiency	Shorter RT
Increase in DBP	Lower accuracy	No effect	Shorter RT
Lowering of HR	Lower accuracy	No effect	Shorter RT
Increase in O_2 intake	No effect	No effect	No effect

*simple reaction time, **=code substitution, code-substitution delayed, logical reasoning, continuous performance, matching to sample, Sternberg 6

5.4 Postural control during single and repeated exposures to cold (V)

Postural sway was markedly increased by exposure to cold, as indicated by the significantly higher path length, area, forward-backward movement and velocity ($p<0.05$-0.01). Side-to-side-movement was not affected by cold exposure. For example, at 10°C the total path length increased by 62-87% (eyes open, EO) and 51-65% (eyes closed, EC) (Fig. 4) compared with 25°C (Study V, Table 1). Closing the eyes increased path length, sway area and velocity of the movement significantly compared with EO. Furthermore, when the subjects closed their eyes path length, velocity and total area remained significantly higher at 10°C compared with 25°C ($p<0.05$). This effect was abolished over the 10-day exposure period, and no significant differences between 10°C and 25°C in any of the sway parameters were observed by Day 10 with EC.

When examining the effect of repeated exposures at 10°C, we observed that forward-backward, side-to-side movements and the total area of sway decreased significantly over the 10-d period (Study V, Fig.1). The decrease in sway was 10-40%, both at 25°C and 10°C and tended to stabilise most often from day 4-5 onward. The reduction in sway over the exposure period at 10°C was not so clear at EC. When comparing the change in sway between the two temperature conditions (25°C vs. 10°C) on Days 1, 5 and 10, no significant differences were observed.

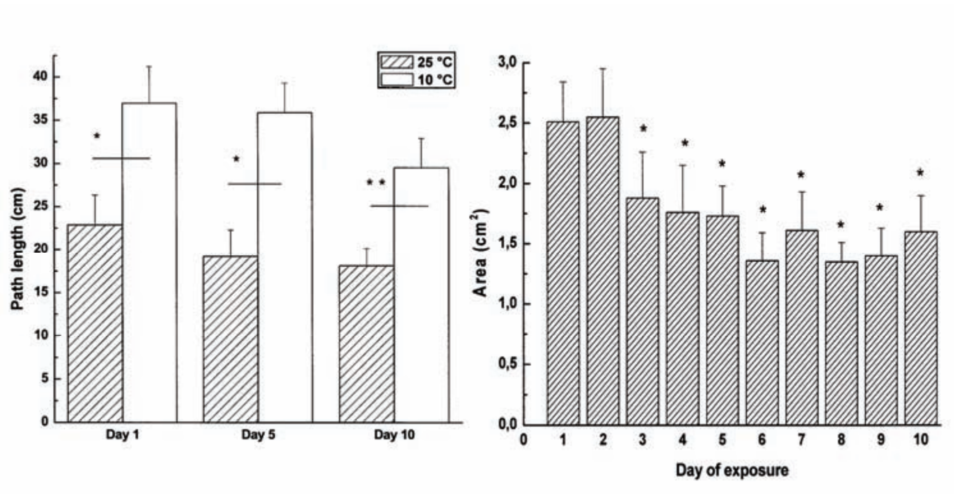

Fig. 4. (Left panel) Path length (cm) at 25°C and 10°C during days 1, 5 and 10. (Right panel) Sway area (cm^2) during the 10-d exposure. Values represent mean±SE (n=10).

6 Discussion

6.1 Cold exposure at the population level (I)

The present study is the first population-based study covering a broad age range to describe the duration and factors affecting outdoor exposure to cold. It was assumed that outdoor exposure in winter is affected by occupational, individual and behavioural factors.

The study demonstrated that most of the cold exposure occurs in certain outdoor occupations and during leisure time, where cold exposure may be significant. However, Finns are on average exposed to cold for relatively short periods. The self-reported total outdoor exposure time during winter, including both occupational and leisure-time exposure, was on average 7 h per week (60 min per day), accounting for 4% of the total weekly time. This corresponds relatively well with studies assessing human activity patterns, most often based on 24 h-diary recalls, which have demonstrated that people spend 6-7% of their time outdoors and the rest of the time indoors or in vehicles (Klepeis *et al.* 2001, Leech *et al.* 2002). Most of the exposure to cold occurred during leisure time (71%); occupational exposure to cold accounted for 4%, and time spent commuting to work for 14% of the total cold exposure. The self-reported cold exposure in the present study is consistent with population surveys where the total amount of cold exposure among people aged 50-74 years and residing in Europe or Russia ranges between ca. 30-80 min per day (Donaldson *et al.* 1998a, Donaldson *et al.* 1998b, Donaldson *et al.* 2001).

The self-reported average leisure-time cold exposure (34-43 min per day) corresponds relatively well with national and international surveys where ca. 30-60 min per day is used for leisure-time activities (Pivarnik *et al.* 2003, Statistics Finland 2005). In the present study, men reported being more exposed to cold during leisure time than women, which is also consistent with the results of the national survey on time use (Statistics Finland 2005). This phenomenon may partially be explained by cultural differences and preferences. Factors associated with more cold exposure during leisure time in men and women were most clearly related to reported occupation and the level of physical activity. Ageing was associated with less cold exposure during the leisure time in women, and within the oldest age group (65-74 years) of men. This could indicate a tendency to avoid cold exposure due to increased prevalence of diseases, poorer health or physical fitness related to ageing. For example, an increased prevalence of cold-related symptoms and complaints has been observed with advancing age (Hassi *et al.* 2000b, Rytkönen *et al.* 2005). Due to co-morbidity elderly people often report being more "weather sensitive" (Von Mackensen *et al.* 2005), which could also affect their decision to be engaged in outdoor activities. Furthermore, a recent study demonstrated that exacerbation of chronic obstructive pulmonary disease decreased the overall time spent outdoors (Donaldson *et al.* 2005). In the present study, of the different occupational groups housewives, pensioners (aged over 63 years) and unemployed persons spent significantly more time outdoors engaged in leisure-time activities. Furthermore, persons exercising at least to some degree were more exposed to cold. Among men, improved health and college-level or vocational education was also associated with more leisure-time cold exposure. Interestingly, men employed in occupations where the amount of cold exposure is significant also spent more time outdoors during their leisure time. The fact that no association between self-rated health and leisure-time cold exposure in women was detected could partially be explained by selection, which may have excluded those women having the poorest health from the study.

Of men, 57% reported being exposed to cold at work for more than 10 hours per week. Most of the occupational cold exposure was reported to occur among agriculture, forestry, mining industry, factory work, construction work and related occupations. On average, women were exposed to cold at work 3-4 hours less per week than men, and many of them (20%) reported being exposed to cold less than 1 h per week. The average occupational exposure to cold of the entire study population was 0.3 h per week, which indicates that the majority of Finns are employed in indoor occupations. When examining the independent factors explaining occupational cold exposure, most of it occurred among working-aged men (>25 years) who had elementary school or vocational education. A small population of men and women living in the archipelago were more exposed to cold than those living in urban areas, probably because occupations such as fishing and agriculture are concentrated in these areas. Self-rated health did not explain the amount of occupational cold exposure in men, which could be due to the fact that, in general, healthier workers are selected to occupations that are physically more demanding and where most of the cold exposure occurs.

Women reported being more exposed to cold while commuting to work. This may be related to socio-cultural aspects and values, so that women tend to prefer walking, cycling or taking the bus to work. Factors associated with a higher amount of cold exposure while travelling to work were being working-aged, living in urban areas, being a student and being physically active. On average, the self-reported amount of cold exposure while commuting to work was short, only 1 h per week, meaning 12 minutes/day.

The measured temperatures were not clearly associated with self-reported outdoor cold exposure. The inability to detect such an association is not very surprising, as a previous study conducted in Siberia demonstrated that there is a reduction in outdoor excursions only when the temperature falls below -20°C (Donaldson et al. 1998a). It should also be noted that the self-reports represent average exposure times. Furthermore, a marked variation in cold temperatures occurred during the study period.

With regard to possible health effects, our study demonstrates that cold exposure is significant in certain outdoor occupations and during leisure time. A more considerable amount of cold exposure is associated with increased prevalence of cold-related symptoms (Rytkönen *et al.* 2005) and morbidity in the winter (e.g. Spencer *et al.* 1998, Danet *et al.* 1999, Näyhä 2002, Hajat *et al.* 2004) and could also result in cold injuries (Hassi & Mäkinen 2000). Especially persons suffering from cardiovascular or respiratory diseases are more susceptible to adverse cold effects. It is also well known that cardiovascular and respiratory diseases are the main cause for excess winter mortality, which means 2,000-3,000 additional deaths during the cold season in Finland (Näyhä 2005). This affects the elderly population in particular, but also ca. 20% of those of working age (Näyhä 2005). Lower socioeconomic status may partially protect working-aged men from adverse cold effects (Donaldson & Keatinge 2003), but not retired age groups or elderly women. A recent study suggests that especially elderly women are vulnerable to the adverse effects of cold (Wilkinson *et al.* 2004). However, it should be noted that in Finland the increase in mortality with a decrease in temperature is lower than in countries in southern parts of Europe (The Eurowinter group 1997), which can partially be explained by behavioural factors, such as better protection of extremities (Donaldson *et al.* 2001).

The present population study did not include younger age groups (adolescents). A previous study conducted among school children aged 14-18 years indicated that 37% of boys and 23% of girls spend more than 12 h per week outdoors during winter (Juopperi *et al.* 2003). It should be noted that in the same study 18.3% of the boys and 11.3% of the girls reported having had a blister-grade frostbite during their lifetime. This indicates that regular exposure to cold, and especially physical exercise in winter, is associated with adverse health effects. Furthermore, one occupational group not included in the study was military personnel. The duration of outdoor cold exposure in winter during military training can be significant, equalling or exceeding that of other cold outdoor occupations. In these conditions, adverse performance effects (Rintamäki *et al.* 2004) and cold injuries (Hassi *et al.* 2005) are common.

One limitation of the study is that the self-reported outdoor exposure was assessed in a retrospective manner reflecting the average situation of the past winter. Compared with 24-h recalls, for example, this may have caused some inaccuracies to estimates of the duration of cold exposure. However, our analyses did not detect any correlation between the time of data collection and reported cold exposure.

With regard to cold exposure, special attention should be given to the prevention of possible adverse cold effects occurring in outdoor cold occupations and leisure time, where the amount of cold exposure is significant. Furthermore, cold risk management measures should be focused on special population groups, such as the elderly, who are at higher risk for the adverse effects of cold exposure. Descriptive information of population-based cold exposure can be utilised when developing probabilistic population exposure models. Further studies are needed to combine information on cold exposure with health measures.

6.2 Cold adaptation

6.2.1 Seasonal changes in thermal responses (II)

The hypothesis of the study was that, because of usually short cold exposure periods in winter (Study I), causing only superficial and peripheral cooling, habituation with dampened responses to cold would occur. In the present study seasonal differences in skin temperature, M, circulation and thermal sensitivity were observed. However, these responses did not resemble the blunted responses associated with cold habituation caused by repeated exposures to cold air or water, such as dampened thermal sensations, blunted vasoconstriction and M (Brown & Page 1952, Radomski & Boutelier 1982, Leftheriotis *et al.* 1990, Hesslink *et al.* 1992, Castellani *et al.* 1998). Instead, there were signs of enhanced responses especially in the peripheral areas of the body, indicating improved preservation of body heat. In addition, the present study showed that the diurnal thermal responses were similar in both seasons. Consistent with a cold-water immersion study (Castellani *et al.* 1999), no differences were observed in thermal responses (except for T_{rect}) during the daytime.

The main observations were that skin temperatures decreased more pronouncedly in most measured sites in winter than in summer. At the same time, blood flow in the fingers was more reduced in winter, indicating enhanced vasoconstriction. The observed peripheral vasoconstriction is in accordance with some studies where lowered finger temperatures were observed after an Arctic exercise (Livingstone 1976) and in urban subjects in winter (Hisdal & Reinertsen 1998). However, in general acclimatisation of the peripheral areas of the body is associated with higher skin temperatures, improved circulation and an earlier onset of CIVD (Brown & Page 1952, Krog *et al.* 1960, Nelms & Soper 1962, Leftheriotis *et al.* 1990, Purkayastha *et al.* 1992, Rintamäki *et al.* 1993, Daanen 2003). The overall enhanced cooling of the skin observed in the present study could indicate preservation of heat by vasoconstriction, resembling an insulative type of acclimatisation. This type of response could develop due to repeated, relatively intense cold exposures, which mainly affect the face and extremities. Exposure of the face alone to cold, possibly combined with wind, is a marked stimulus for an increased BP and a strong sympathetic response (Gavhed *et al.* 2000). Bittel (1987) suggests that a lowering of heat debt in cold can be considered an index of cold adaptation. However, this type of response is usually demonstrated in association with repeated cold exposures causing marked whole-body cooling (Young *et al.* 1986, Bittel 1987, Budd *et al.* 1993). Considerable whole-body cooling is not likely to occur in these urban subjects, where cold exposure occurs for relatively short periods, mainly while commuting to work or during leisure-time activities as shown in Study I. Another explanation is that the more considerable decrease in skin temperature is a sign of an aggravated reaction towards acute cold exposure, indicating lack of habituation or other type of cold adaptation. In the present study also a significantly higher M in winter compared with summer in response to the cold exposure was observed. This result is consistent with the study by Van Ooijen *et al.* (2004) who exposed subjects living in the Netherlands to mild (15°C) cold exposure during winter and summer. They suggested that the increased M was due to metabolic acclimatisation. However, most often this type of acclimatisation is observed due to cold exposures causing repeated substantial whole-body cooling (Scholander *et al.* 1958b, Hammel *et al.* 1960). Rather, the increased M in the present study may reflect an aggravated response to the more pronounced cooling of the skin in the population measured in winter.

The present study also examined thermal sensitivity, sensations and comfort. The perception of thermal stimuli is fundamental for judging thermal comfort or discomfort. Cold sensitivity in the hand was impaired in the cold environment, and a temperature drop of 3-4°C from the baseline temperature was needed before the subjects sensed the cold stimulus. This decreased cold discrimination was more pronounced in winter than in the summer and was correlated with the lower hand temperatures (1.8°C) measured in winter. It is possible that this magnitude of cooling, which is below the maximum static discharge frequency for cold receptors, may increase the threshold for discriminating incremental changes in temperature (Kenshalo 1970, Johnson *et al.* 1973, Hensel 1980). Cold exposure or season did not affect warm sensitivity. Overall, subjects measured in winter reported slightly more intense cold sensations and subsequent discomfort than they did in the summer. The observed differences in thermal sensations were minor and do not have much practical relevance. However, the result further suggests that no habituation to cold in thermal sensations occurred in the winter, and is in agreement with the observed thermal responses.

Only a few studies have examined seasonal difference in thermal responses in urban populations. In summary, these have shown divergent results and resulted in different interpretations with regard to whether cold acclimatisation, and what type of it, occurs in urban residents. Davis and Johnston (1961) measured cold responses at 14°C of indoor workers in Kentucky, USA at 1-month intervals in summer and winter. They demonstrated a gradually decreasing VO_2 and shivering from winter to summer, but unaltered skin or rectal temperatures. LeBlanc *et al.* (1975) determined autonomic nervous system responses in Canadian mailmen and found a diminished vasopressor response at the end of winter suggesting cold habituation. The previously mentioned study by Van Ooijen *et al.* (2004) observed an increased response in M but unaltered skin temperature in winter compared with summer when subjects were exposed to 15°C. On the other hand, Inoue *et al.* (1995) did not detect seasonal differences in M or T_{sk} in young Japanese subjects exposed to mild (17°C) cold. However, older subjects had a significantly higher M in summer and autumn compared with winter and spring. Lee *et al.* (1993) detected lower skin temperatures and higher M in response to cold in subjects measured during summer compared with winter. A hypothermic response (lowered T_{rect}) towards mild cold (25°C and 15°C) was detected by Li *et al.* (1994) in subjects with uncovered legs when the season gradually became colder. Hisdal & Reinertsen (1998) exposed urban citizens living in Norway (63°N) to local cold (cooling of hand in 7.3°C water). Consistent with our study, they did not observe local habituation. Rather, the CIVD response in fingers was delayed and the magnitude of the response lowered in winter compared with summer.

Altogether, a direct comparison of the results of these studies is difficult due to the different cold exposure protocols. Marked individual differences in the types of responses (e.g. insulative or metabolic) are also often observed (Van Ooijen *et al.* 2004), which are probably related to both the individual's physical characteristics (Van Marken Lichtenbelt *et al.* 2002), but also to the type and amount of cold exposure the person has been exposed to in his/her habitual activities. Climatic influences (severity of winter) could also affect the resultant cold acclimatisation pattern. Compared with the other studies, our research was conducted in a high latitude environment (65 °N) characterised by cold environmental conditions in winter; however, no responses characteristic of cold habituation were observed.

The lack of typical cold habituation responses in winter may be explained by behavioural factors. Urban residents are able to minimise their cold strain by several means. The use of adequate winter clothing prevents marked cooling and adverse cold effects. Especially northern inhabitants tend to protect their extremities more efficiently than people living in warmer regions with a given fall in temperature (Donaldson *et al.* 2001). Other factors minimising the cold strain are the relatively short cold exposure periods experienced only while commuting to work, or during leisure-time activities as was shown in Study I. In addition, constantly high indoor temperatures in homes and office buildings, with an average of 21°C in northern Finland during winter (The Eurowinter group, 1997), decrease the cold strain. It is therefore possible that repetitive marked cooling of the skin occurs rarely in winter. These results are representative for people employed in indoor occupations, and it is probable that the cold acclimatisation profile is different in outdoor occupations, where repeated exposures to cold occur for several hours a day. In these conditions peripheral cooling is common (Virokannas 1996), and whole-body cooling may also occur.

The results of the study should be interpreted with some caution, as it was a deficiency of this study that, due to the laborious and demanding experimental design, we were not able to measure the same individuals in both winter and summer as was initially planned. Thus, a pair-wise statistical comparison was not possible. We aimed to reduce the effects of individual variation on the thermal response by careful selection of the subjects to match the anthropometric parameters between the study populations as closely as possible. In addition, for each individual we examined the effects of anthropometry on the thermal responses (see Study II), and produced individual plots of the thermal responses to confirm the consistency of the findings. From a statistical perspective the relatively small sample size may have precluded our ability to have sufficient power to rule out a Type II error. This could in some cases have resulted in an underestimation of potential physiologically meaningful changes.

6.2.2 Effect of cold acclimation on thermal responses (IV, V)

Exposing subjects to cold for a 10-d cold period resulted in blunted thermal responses indicating cold habituation. Consistent with previous studies thermal sensations became less intense and habituated quickly, after 1-2 days of exposure in either cold air or water (Brück *et al.* 1976, Jansky *et al.* 1996, Leppäluoto *et al.* 2001, Smolander *et al.* 2004). The change in thermal sensations was rather similar to the previous studies (ca. one point in the scale). At the same time the subjects experienced slightly less cold discomfort. It is possible that the less intense cold sensations could be due to synaptic depression in neural connections between the hippocampal and cortical areas (Ganong 2003).

The observed dampened M suggests shivering habituation and is consistent with other studies where humans have been exposed to cold air for repeated, relatively short periods (Brück *et al.* 1976, Silami-Garcia & Haymes 1989, Hesslink *et al.* 1992). The higher skin temperatures (whole body, peripheral) indicate a dampened vasoconstriction. In a similar cold exposure protocol as ours, Leppäluoto *et al.* (2001) observed locally increased skin temperatures of 1.5-2.0°C (forearm) due to repeated exposures. However, in contrast to their study where the increase in skin temperature was abolished in the end part of the 10-d exposure, in our study T_{sk} increased throughout the exposure period in a consistent manner. No changes in T_{rect} were observed, similarly to studies using short (20 min-2 h) repeated exposure periods (Hesslink *et al.* 1992, Leppäluoto *et al.* 2001). A lowering of T_{rect} (hypothermic habituation) requires repeated exposures lasting several hours or days (Kreider *et al.* 1959, Keatinge 1961).

The significantly smaller NA response to cold suggests diminished sympathetic activity and habituation of the autonomic nervous system (Leppäluoto *et al.* 2005). The finding is consistent with previous studies exposing subjects repeatedly to cold (Radomski & Boutelier 1982, Hesslink *et al.* 1992, Leppäluoto *et al.* 2001). The diminished sympathetic response results in less intense peripheral vasoconstriction (leading to higher skin temperatures), and is also reflected as lowered BP responses that were especially evident in the beginning of the cooling phase.

Overall, the most marked changes in thermal responses caused by cold acclimation could be seen in the initial cooling period (first 30 min of cold exposure). By the end of the exposure period (120 min) the changes in thermal responses tended to even out, and the differences between a non-cold acclimated and acclimated subject were smaller.

6.3 Performance

6.3.1 Seasonal effects on cognitive performance in cold (III)

It was hypothesised that pronounced changes in photoperiod and T_a occurring in a northern climate, like Finland, could through altered endocrinological responses result in more negative mood states in winter (Palinkas 2003) and an impaired cognitive performance. However, the results did not support this hypothesis for urban subjects, and no marked seasonal effects on cognitive performance during cold exposure were observed. Based on the completed Profile of Mood States (POMS) questionnaires (results not presented), the winter season was associated with more depression and forgetfulness, but no changes in the other parameters reflecting mood disturbances. Of the cognitive tasks, only two tests showed seasonal differences: the repeated acquisition task was performed more accurately in the winter and the addition-subtraction task in the summer compared with the other season. After controlling for test condition, sequencing of day and the time of day, season was not associated with accuracy in any of the five cognitive tasks. Only RTs were longer in summer in two tasks (simple RT, grammatical reasoning). Thus, these differences do not allow making any far-reaching conclusions supporting seasonal effects. These results are in line with the work by Brennen *et al.* (1999) who found no evidence of impaired cognition in winter; performance was rather improved compared with summer in residents living in northern Norway. Otherwise, there are only a few studies where seasonal changes and cognition have been examined. Michalon *et al.* (1997) reported deficits in recognition memory and recall in SAD patients compared to controls measured in three consecutive winters. However, no comparison to summer was made. Drake *et al.* (1997) reported that cognitive performance was improved in summer in the Stroop test. The lack of association between season and cognition in our study could be supported by the fact that in contrast to outdoor workers residing in northern Finland (Hassi *et al.* 2001), no marked seasonal differences in thyroid hormone concentrations in young urban subjects were detected in our study (unpublished result). The lack of seasonal changes in thyroid function and cognition in these urban subjects further indicates that the cold exposure had been short (Study I) and probably insufficient to cause repeated cooling and changes in thermoregulation, metabolism or secretion of hormones (Study II).

The present study also examined the separate and combined effects of cold and the amount of light on cognition. Interestingly, as the conditions became progressively more severe (i.e., moving from warm conditions and bright light to cold conditions and bright light to cold conditions and dim light), less time was used to complete all the cognitive tasks. At the same time, accuracy improved in three tasks and deteriorated in two tasks. Furthermore, a cold environment and a reduction in the level of light was associated with a reduction in negative mood states, for example tension and anger (results not presented). The fact that the tasks were performed faster as well as more accurately (complex tasks) in more severe environmental conditions could support the arousal hypothesis (Payne 1959, Provins *et al.* 1973, Ellis 1982, Ellis *et al.* 1985, Enander 1987, Van Orden *et al.* 1990). It is possible that under the moderate cold exposure (slightly decreased skin temperature but no marked changes in T_{rect}), and with the limited amount of light, arousal was increased to a level which improved performance. Thus, the subjects viewed the cold as a challenge and devoted more attention to the tasks as the environmental conditions became worse.

Cold exposure and the level of light affected the performance of complex and simple tasks differentially. The three tasks exhibiting improvement in accuracy as well as shorter RTs are designed to assess complex cognitive performance in areas of short-term memory, logical reasoning, and executive function. The two tasks exhibiting degradation in accuracy (addition-subtraction, simple RT) are designed to assess less complex elements of cognitive performance in areas of sustained attention and visuo-motor flexibility. Interestingly, performance in complex tasks was improved under cold and cold/dim conditions. This observation differs from some previous studies where especially complex tasks have been shown to be susceptible to both short-term moderate cooling (60-90 min at 5-10°C) (Bowen 1968, Ellis 1982, Enander 1987, Thomas *et al.* 1989) and more severe central cooling (Giesbrecht *et al.* 1993, Lockhart *et al.* 2005). However, it was hypothesised that with moderate cooling a certain level of arousal affects performance of complex tasks beneficially. This is consistent with the finding by Giesbrecht *et al.* (1993) where an initial cooling during cold-water immersion improved performance of complex cognitive tasks (backward digit span, Stroop test), which was eventually followed by a decrease in performance when central cooling progressed. Unexpectedly, the simple tasks were adversely affected by cold so that they were performed faster but less accurately. Most often the simple RT task has shown minimal decrements even under relatively severe cooling (Teichner 1958, Ellis 1982, Hoffman 2001). The addition-subtraction task, which measures sustained attention, was performed less accurately in the cold in the present study as well. A possible explanation for the decreased performance in these two simple tasks could be that as the task does not require that much attention compared with the complex tasks, the cold may be more considerable as a distraction factor.

The differential effects of cold on simple and complex tasks could also be viewed from the perspective of information processing, where a distinction between automated and controlled processing has been made (Shiffrin & Schneider 1977). The former is characterised by fast, and almost limitless capacity in processing information, and requires minimal effort, intention or subjective awareness. Controlled processing, on the other hand, require effort, intention and subjective awareness. Controlled (effortful) and automatic processing appears to regulate different aspects of the stress response (Ellenbogen *et al.* 2006). Cold stress and resulting changes in arousal/distraction could differentially affect these different modes of processing. Though, the exact mechanism remains to be further elucidated.

As was mentioned previously (chapter 6.2.1), the relatively small sample size may have precluded our ability to have sufficient power to rule out a Type II error when examining seasonal differences in cognitive performance. Furthermore, some of the accuracy measures may also have been susceptible to ceiling effects.

6.3.2 Cognitive performance during repeated cold exposures (IV)

The hypothesis of the cold acclimation study was that habituation to cold, leading to less intense cold sensations and discomfort, could affect cognitive performance beneficially. This would occur mainly through the reduction of cold-related distraction. One objective of the study was also to determine further how non-hypothermic cooling would affect complex and simple cognitive tasks and whether the performance strategy (e.g. speed vs. accuracy) would change due to repeated cold exposures. The association between changes in thermal responses and cognition was also emphasised. The study used a different test battery (ANAM) compared with Study III. However, some of the tests in this battery were the same (matching to sample, simple reaction time, logical reasoning). Altogether the tests measured the same elements of cognition in both test batteries.

The cold exposure introduced in this study caused a more intense cooling (ca. 600 kJ decrease in S, 6-7°C in T_{sk} and 0.4°C in T_{rect}) compared with Study III (ca. 350 kJ decrease in S, ~3°C in T_{sk}, unaltered T_{rect}). However, it can still be considered a non-hypothermic and moderate cold exposure, as the decrease in T_{rect} was not substantial. With regard to cognitive performance, slightly different responses compared with Study III were observed. Three distinct patterns of cognitive performance were detected. These were: 1) negative, reflected in increased response times and decreased accuracy and efficiency; 2) positive, reflected in decreased response time and increased efficiency; and 3) mixed, reflected in a pattern of increases in both accuracy and response time and decreases in efficiency, and a pattern of decreases in both accuracy and response time.

With regard to a specific form of cognition (e.g. learning, memory, sustained attention), no clear pattern of the effects of cold could be distinguished. When examining task complexity some differences between simple and complex tasks were again detected. The correlation analyses demonstrated that, consistently with Study III, the simple RT task was again adversely affected by cold. However, in contrast to Study III, the response times were longer in cold, which reduced the overall efficiency. The different results can partially be explained by the variation in the multivariate analyses. In Study IV additional physiological variables were included in the model, which could have accounted for some of the observed differences between the studies.

When examining the thermal and cardiovascular parameters a reduction in skin temperature, cold thermal sensations and an increase in BP were all significantly associated with longer RTs and reduced efficiency in the simple RT task (Table 4, Study IV). Furthermore, in the regression analysis the increase in DBP and decrease in HR were independent predictors of longer RTs and reduced efficiency in the simple RT task. Cardiovascular reactions in response to cold stress thus seem to be connected to impaired cognitive performance.

The observed positive and mixed responses in performance in the cold are consistent with the abovementioned arousal hypothesis (chapter 6.3.1). In the present study a slight reduction in T_{rect} (0.4°C) was an independent predictor of shorter RTs and increased efficiency in all of the cognitive tasks. Consistent with this result, shorter RTs at cold exposures of 4-5°C and lasting for 50-60 min have been demonstrated (Shurtleff *et al.* 1994, Van Orden *et al.* 1996), suggesting faster CNS processing (Van Orden *et al.* 1996). The second pattern of arousal was illustrated by shorter RTs, but also reduced accuracy resulting in unaltered efficiency. This observation is consistent with the studies where shorter response latencies or sample response times, but also an impaired matching to sample accuracy was observed in subjects exposed to 4-5°C for 30-60 min (Thomas *et al.* 1989, Shurtleff *et al.* 1994). In the present study cold sensations in hands, an increased BP and lowered HR predicted this type of response. This could suggest that the subjects were reaching a level of arousal which starts to cause initial performance decrements.

This study was also the first to follow the effects of repeated environmental stress on cognition for a longer time period. Thomas *et al.* (1989) observed that the effect of cold on matching to sample accuracy remained the same over three weekly repetitions. However, no emphasis has been given in previous studies on studying the effects of cold acclimation on cognition. The results of the present study showed that RTs became shorter and cognitive task efficiency improved significantly over the 10-d period both under control and cold exposures, suggesting that learning occurred under both conditions. In some of the tasks, these changes in performance tended to stabilise after approximately five days of exposure. The successive changes in cognitive performance over time did not differ markedly between control and cold. This would indicate that the observed cold acclimation responses during the 10-d period had little, if any, effects on cognitive performance. On the other hand, it is possible that less effort was needed to fulfil the same task in the cold in the end of the acclimation period, due to a lesser amount of cold discomfort. It should, however, be noted that cognitive performance was assessed at the end of each cold exposure. The most marked cold acclimation responses were seen in the beginning of each cold exposure and tended to even out as the cooling progressed. Therefore, in future research it could be of interest to follow the initial cooling period and to assess cognitive performance at repeated intervals.

Altogether, the two studies (III, IV) implicate that moderate cooling (decrease of T_{sk} of ca. 2-3°C) causes some beneficial effects on cognitive performance, especially in complex cognitive tasks. This is manifested as reduced RTs, suggesting an increased arousal. With a slightly more intense non-hypothermic cold exposure (decrease of T_{sk} of ca. 6-7°C), a mixture of different effects on cognitive performance is seen. The negative effects (longer RT) could indicate cold-induced distraction. The positive (shorter RTs, improved efficiency) and mixed effects (shorter RTs, reduced accuracy, unaltered efficiency) could support the arousal hypothesis and indicate that a level of arousal is approached where performance decrements begin to be observed.

Although not studied in detail in the present study, mood and motivation may significantly affect cognitive performance. Mood states are closely connected to the level of arousal (Thayer 1989). Hence, transient mood states could be affected by cold exposure, which changes the level of arousal. Motivation is tied to the distraction and arousal hypotheses and could also affect the performance of cognitive tasks. Highly motivated individuals may be more aroused; on the other hand, greater susceptibility to arousal may be a precursor to motivation. Highly motivated persons are also less susceptible to distraction. It is possible that motivation could mediate the relationship between cold exposure and cognitive performance. However, the association between mood, motivation and cognition in cold warrants further studies.

The observed negative effects of cold exposure on cognition may be of significance in situations requiring decision-making, or in reactions to emergency situations. An impaired cognitive performance could also deteriorate work productivity and safety in occupations requiring vigilance and concentration. Future studies are needed to assess further dose-response relations (e.g. linear, quadratic or other type) between thermoregulation and cognition. Individual characteristics (age, gender) could also affect cognitive performance in cold. Additional research could also be focused on determining the thresholds for cognitive decrements that occur either as a result of distraction or arousal.

6.3.3 Postural control during single and repeated exposures to cold (V)

A sufficient amount of postural control is needed to maintain balance. The importance of sufficient postural control is emphasised in winter, where the risk of falling is aggravated in cold conditions due to slippery surfaces and limited visibility (Gao *et al.* 2004). Maintaining one's balance requires constant fine-tuning of movements as well as concentration. The task itself (standing) is of low physical activity and is susceptible to cooling. It was hypothesised that superficial cooling, especially of the peripheral areas, might impair postural control due to changes in sensory or neuromuscular functions. The second hypothesis was that repeated exposures to cold, causing changes in thermoregulation (cold habituation responses), may improve postural control. This could occur for example due to dampening of shivering and a reduced need for corrective movements. To our knowledge, this study was the first one to assess the effects of cold on whole-body postural control.

The main finding of the study was that cold exposure causes a significant increase in postural sway, indicating impaired postural control. The path length, which indicates the cumulative value of sway, increased by 70-90% in cold, which could indicate that more corrective movements are needed to maintain balance in cold. The loss of visual information when closing the eyes increased sway further, demonstrating the importance of vision in postural control. When closing the eyes the effect of cold on sway was less marked, possibly due to the fact that sway was already increased by the lack of visual information, partially masking the effects of cold.

We detected a decrement in postural sway over the 10-d period. On average the different sway parameters decreased by 10-40%, indicating motor learning. However, the changes in sway over the 10-d period was similar at 25°C and 10°C, implying that the observed cold habituation responses had little, if any, effects on sway. The increased muscle tone and shivering in the cold was not consistently associated with sway, nor did shivering intensity diminish over the 10-d period. It is possible that the measured shivering during the sway tests could have been momentarily suppressed due to focusing on the task, as has been shown to occur during short-term tasks, such as breath holding and arithmetical tasks (Israel *et al.* 1993).

Although the present study did not examine the mechanisms for the increase in sway in cold, it could be hypothesised that the impaired postural control could be due to a combination of changes in sensory, neural or motor functions due to cooling. Of the sensory elements, cooling can affect the ankle mechanoreceptors (Magnusson *et al.* 1990, Stal *et al.* 2003) or the proprioceptors located in the muscles, tendons and joints. Alterations in muscle spindle activity due to cooling can suppress tendon-reflex amplitudes, consequently affecting neuromuscular control (Oksa *et al.* 2000). The neural transmission of both afferent and efferent information may also be slowed down due to cooling of the nerves (Rutkove 2001). Furthermore, the effects of cooling on the functional properties of the muscles could render the fine-tuning of movements when maintaining balance more difficult (Oksa *et al.* 1995, Oksa *et al.* 1997). Although EMG activity was not consistently associated with sway, it is still possible that the increased muscle tone could affect postural control. Cooling has been shown to increase the viscosity in the synovial joints (Hunter *et al.* 1952), which could also affect regulation of body posture. Finally, the effects of cold as a discomfort and distraction factor should not be forgotten, either. Anxiety and adverse mood effects have been shown to alter postural control, possibly by interfering with sensory processing (Bolmont *et al.* 2002).

The finding of increased sway in the cold may be important to recognise during leisure-time or occupational activities performed in cold environmental conditions. Persons that are at higher risk of falling may be especially susceptible to the effects of cooling due to changes in their postural control. These population groups include the elderly and/or persons having impaired balance due to a neurological or musculoskeletal disorder (Gao *et al.* 2004, Demura *et al.* 2005, Korpelainen *et al.* 2005, Piirtola & Era 2006). For example, changes in lateral postural control may predict subsequent falls in the elderly (Piirtola & Era 2006). Further studies are needed to examine the mechanisms related to the impaired postural control in the cold. Particularly those population groups that are at higher risk of falling should be examined in this respect.

7 Conclusions

In the Finnish population, residing in a northern climate, the average outdoor cold exposure in winter was 4% (7 h per week) of the total weekly time. Most of the cold exposure occurs during the leisure time. Occupational exposure to cold is significant among agriculture, forestry, mining, factory work, construction work and related occupations, and 57% of men reported being exposed to cold more than 10 h per week. However, the average duration of cold exposure at work is relatively short or lacking. Men are more exposed to cold than women both during their occupational and leisure-time activities. Factors explaining increased cold exposure at work were: being employed in outdoor occupations, age and a lesser amount of education. Factors associated with more leisure-time cold exposure were: being employed in outdoor occupations, being a pensioner, housewife, unemployed, practising physical exercise, and reporting at least average health.

While exposed to cold, seasonal differences in skin temperature, metabolic rate, circulation and thermal sensitivity were observed in northern urban residents. The observed thermal responses did not resemble cold habituation responses typical of cold acclimatisation. Rather, they resemble aggravated reactions in non-cold acclimatised subjects towards acute cold exposure. It is possible that the cold-protective clothing used, short cold exposure periods and high housing temperatures in winter prevent the development of cold habituation.

Exposure to non-hypothermic cold exposure resulted in positive, negative and mixed effects on cognition. The effect of cold on cognitive performance was similar in both seasons. Different effects of moderate cold on simple and complex tasks were detected. Simple tasks were impaired in cold, while in complex tasks both positive, negative and mixed effects were observed. Repeated exposures to moderate cold resulted in learning, which occurred to the same extent as in a warm environment. The observed cold habituation responses did not affect cognition. It is suggested that moderate cold exposure affects cognitive performance through different mechanisms related to either distraction or through different patterns of arousal caused by the cold exposure.

Whole-body exposure to cold, causing superficial, but no marked deep body cooling, increases postural sway considerably, indicating an impaired postural control. Sway increased on average by 70-90% in cold. It is possible that more corrective movements are needed to maintain balance in the cold due to changes in sensory functions or neuromuscular control. The finding of an increased sway in cold may be significant especially in persons that are at higher risk of falling. Such population groups are for example elderly people, or persons having impaired balance due to a neurological or musculoskeletal disorder.

The present study provides new information of the cold exposure and acclimatisation patterns of northern residents as well as its functional significance on selected performance measures. The information from population-based cold exposure can be utilised when developing probabilistic population exposure models. Knowledge on the effects of acute and repeated exposures to moderate cold on psychological and physical performance is usable when producing occupational health care and safety strategies for cold work. The information may also be utilised for developing monitoring systems predicting cold hazards. Health care targeted to special population groups at higher risk for adverse cold effects can implement the knowledge in their practices.

Further modelling is needed where the interrelations between cold exposure, thermoregulation, endocrinology and performance (psychological, physical) are analysed in conjunction with each other. These models should also aim at including the effects of individual characteristics.

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Appendix 1

Table A1. Summary of studies (in alphabetical order) examining the effects of cold exposure on different forms of cognition (vigilance, reaction time, target tracking and memory).

Study	Cold exposure/clothing	Thermal responses	Cognitive task	Effects of cold
Baddeley *et al.* (1975)	60 min dive at 4.4-5.6°C, wetsuits	T_{rect} decreased 0.7°C	Reasoning, vigilance, memory	Deteriorated memory, no effect on reasoning or vigilance
Bowen (1968)	Exposure time varied, 8°C water		Clock test (short-term memory)	22% decrement in short-term memory
Coleshaw *et al.* (1983)	About 60 min at 15°C water	T_{aur}*decreased at max 3.3°C, inter-individual differences	Memory test, simple arithmetic test, logical reasoning	Memory impaired when T_{aur} below 36.7°C, severely impaired when T_{aur} 35°C. Speed of calculation decreased, no effect on accuracy
Davis *et al.* (1975)	40 min dive at 20°C and 5°C, scuba equipment	T_{sk} 21.5°C and T_{rect} 36.8°C	Arithmetic, logical reasoning, digit span, memory and manual dexterity	Impaired arithmetics, logical reasoning, word recall and recognition performance
Ellis (1982)	1.5-2 h at -12°C, shorts	T_{sk} 21°C and T_{rect} to 36.3°C	SCRT**, simple RT, Stroop word colour test, verbal reasoning	Reduced accuracy in SCRT (200-300%), no effects on Simple RT and Stroop test, slightly better reasoning in cold
Ellis *et al.* (1985)	Fast cooling: 40 min -5°C, Slow cooling: 3 h at 8°C, shorts	Fast cooling: T_{sk} 23°C, T_{rect} 37°C Slow cooling: T_{sk} 22.9°C, T_{rect} 36.5°C	SCRT, Raven's Progressive Matrices	Reduced accuracy in SCRT (especially 8-choce task) when rapidly cooled, faster response times
Enander (1987)	60-90 min, 4-5°C, underwear, quilted trousers and jacket	T_{sk} 28-33.2°C, T_{rect} dropped 0.3°C (exp 1), 0.5°C higher (exp 2)	Colour word vigilance, Simple RT, Key tapping, digit addition, digit classification	More errors in tasks requiring rapid responses

Study	Cold exposure/clothing	Thermal responses	Cognitive task	Effects of cold
Giesbrecht *et al.* (1993)	55-80 min 8°C water	T_{core} decreased by 2-4°C	Auditory attention, Benton visual recognition test, forward and backward digit span, Stroop test	Central cooling impaired complex tasks (Stroop test, backward digit span) but not simple tasks
Langkilde *et al.* (1973)	2.5 h at 18.6°C, cotton uniform (0.6 clo)	T_{sk} 32.4°C, T_{rect} 36.7°C	Arithmetic, word memory, clue-utilisation test	No effect of mild cold on performance
Lockhart *et al.* (2005)	max 65 min 10°C water or until T_{es} <34°C	T_{es} dropped to 33.5-34°C	Logical reasoning, Stroop-word color test, digit symbol coding, backward-digit span, paced auditory serial addition test	Decreased performance with central cooling in Stroop test (longer RT), more errors in digit symbol coding, backward digit span and PASAT-test
Marrao *et al.* (2005)	9-d winter survival course, T_a -24 to 4°C, winter clothing	No change in T_{core}, decreased T_{fing}	Logical reasoning, vigilance, planning test	No effect on cognition
Payne (1959)	Three conditions: 3 h 20 min at either 4°C, 13°C or 21°C, indoor clothing (1 clo)	Not measured, visual observations of shivering	Complex visual display task	Decreased tracking proficiency in cold, optimal functioning at 13°C
Pease *et al.* (1980)	Local cooling of hands and arms with ice for 30 min	Not measured	Reaction to light stimulus and completing a co-ordinated movement	Increased reaction time with locally cooled subjects
Shurtleff *et al.* (1994)	60 min at 4°C (cognitive test performed after 30 min exposure)	Not measured	Delayed matching to sample	Impaired working memory in cold, faster response times
Stang & Weiner (1970)	5 x 90 min at 10, 15.5 and 21°C water, wet suits and SCUBA equipment	T_{sk} about 25-28°C at T_w 10-15°C, T_{rect} not measured	Seven different underwater tasks, choice reaction time/simple mental arithmetic	Increased response time in cold to complete underwater assembly tasks

Study	Cold exposure/clothing	Thermal responses	Cognitive task	Effects of cold
Teichner (1958)	45 min rest + 65 min exercise at T_a's of 15.6- -37°C and wind speeds 2-8.9 m/s, nude or arctic clothing	T_{sk} 26.8-32.7°C, T_{rect} not measured	Reaction to verbal and light signal following a psychomotor task	Increased reaction time when wind speed ≥ 4.5 m/s at low ambient temperatures (-26°C)
Thomas *et al.* (1989)	90 min at 5°C, repeated three times	T_{sk} 21.7°C, T_{rect} 37.6°C, reported shivering	Matching to sample task	Impaired working memory in cold (decreased accuracy), choice reaction time longer, sample responses shorter
Van Orden *et al.* (1990)	50 min at 4°C, shorts, t-shirt, socks	No change in T_{rect}	Visual, auditory event-related potentials, brainstem-auditory-evoked responses	Evoked potentials in cold showed shorter latencies=faster CNS processing
Van Orden *et al.* (1996)	60 min at 4°C, shorts, socks, t-shirt	Not measured	A 54-min military scenario task, complex cognitive functioning (command & control)	Less responses to scenario-following commands, greater tendency for mistakes
Vaughan (1977)	3 h at 15.5 and 4.5°C water, wet suits	T_{core} 36.7-36.8ºC, local skin temperature decreased down to 22.9°C	arithmetic task, target detection, navigation	Increase in visual detection times in both temperatures

*aural temperature, **Serial choice reaction time

Original papers

I Mäkinen TM, Raatikka VP, Rytkönen M, Jokelainen J, Rintamäki H, Ruuhela R, Näyhä S & Hassi J Factors affecting outdoor exposure in winter: population-based study. Int J Biometeorol, in press.

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ISBN 951-42-8088-1 (Paperback)
ISBN 951-42-8089-X (PDF)
ISSN 0355-3221 (Print)
ISSN 1796-2234 (Online)