Manual Performance Deterioration in the Cold

Prof. H.A.M. Daanen, Ph.D.
TNO Defence, Security and Safety,
Business Unit Human Factors
PO Box 23, 3769 ZG Soesterberg, The Netherlands

hein.daanen@tno.nl

ABSTRACT

Manual performance during military operations in cold and windy climates is severely hampered by decreased dexterity, but valid dexterity decrease predictors based on climatic factors are scarce. Therefore, this study investigated the decrease in finger dexterity for nine combinations of ambient temperature (-20, -10 and 0°C) and wind speeds (0.2, 4 and 8 m·s^{2}), controlled in a climatic chamber. Finger dexterity was determined by the Purdue pegboard test. Twelve subjects with average to low fat percentage were exposed to cold air for one hour with and without extra insulation by a parka. The subjects were clothed in standard work clothing of the Royal Netherlands Air Force for cold conditions.

Extra insulation did affect cold sensation but not finger dexterity. The deterioration in finger dexterity depended upon Wind Chill Equivalent Temperature (WCET) and the square root of exposure time (r=0.93 for group average). A simple model is constructed that may be valuable to predict the risk for strong dexterity decrease during military operations in the cold, but more work should be done to determine critical values in dexterity for a wide variety of operational tasks.

1 INTRODUCTION

Decreased dexterity is a major problem for military operations in the cold. Manual task performance deteriorates and therefore the number of accidents increases in the cold (1). Also, the safety of others can be compromised, for instance an aircraft loading crew that is seriously affected by cold can unintentionally threaten the safety of the flying personnel. Therefore, directives are needed to indicate when a decrease in manual performance is to be expected so that a fresh crew can take over in time. Factors influencing the exposure time are 1) climatic factors: ambient temperature, wind speed, relative humidity, solar radiation; 2) personal factors: fat insulation, susceptibility to cold, acclimatization; 3) metabolic rate; 4) clothing insulation.

It would be unachievable to vary all these factors in a single experiment; therefore we determined the most critical factors for a study aimed to quantify the dexterity decrease in the cold. We decided to vary two climatic factors and clothing insulation and to take the worst case for personal factors (less than average fat percentage, not previously exposed to cold) and metabolic rate (sitting in rest).

Since the humidity content in cold air is low, this factor was left out. Steadman (2) previously estimated the impact of solar radiation, so the remaining thermal factors included in the analysis are ambient temperature and wind speed. These two factors are combined in the Wind Chill Index (WCI) or Wind

Chill Equivalent Temperature (WCET).

The WCET is commonly used as an estimator for the risk for freezing cold injuries (3;4) but it is also used to estimate cold related mortality (5) and dexterity decrease (6;7). Siple and Passel (3) first introduced the WCI-term based on empirical data. Using the WCI, the 'subjective' temperature ‘WCET’ could be calculated for a chosen reference wind speed. Later, Steadman (2;8) calculated the WCET based on models of human heat transfer. For several decades these two wind-chill indices were used simultaneously with resulting confusion.

In 2001 the National Weather Service (NWS) adopted a new WCET (see www.weather.gov/om/windchill) based on experimental work on facial cooling (9). This WCET is defined as:

$$WCET = 13.12 + 0.6215*T - 11.37*v0.16 + 0.3965*T*v0.16 \quad (10)$$

in which WCET stands for Wind Chill Equivalent Temperature in °C, T for ambient temperature in °C and v for wind speed in km/h measured 10 meters above the ground.

This new WCET is rapidly becoming the ‘de facto’ standard, even though there are still some arguments that the convective heat loss model of the new WCET should have been better established prior to the introduction of this standard (11). Several meteorological offices worldwide changed to the NWS-index and ISO adopted the formula as the indicator for freezing cold injuries (10). Daanen (6) related his observations on dexterity decrease to the Siple/Passel and Steadman formulae, but not to the new NWS-index.

Therefore, it is the aim of this study to investigate the relation between dexterity decrease and the NWS-WCET, so that the WCET-values communicated by the meteorological offices can be used in the field as an indicator for expected dexterity decrease. We hypothesize that the dexterity decrease is strongly related to the WCET and that clothing insulation also explains part of the variation.

2 METHODS

2.1 Subjects

Twelve healthy males (27 ± 6 (SD) years old, 184 ± 8 cm tall and a body mass of 76 ± 12 kg), not exposed to cold for several weeks, participated in the study. The subjects were fully informed of the purpose of the study and of their right to withdraw from experimentation at any time without prejudice and gave their written consent. The Local Ethical Committee approved the protocol.

The subjects participating in the experiment were selected in such a way that their average fat percentage was just below average. The fat percentage of the subjects was 13.5 ± 4.8%. According to Fox and Mathews (12) the average for males is about 15 tot 17%. The subjects performed no exercise and were asked to sit quietly in order to reduce metabolic, heat production. In this way a worst-case situation was constructed. Therefore, the resulting cold exposure times based on this population will be ‘on the safe side’ for the ‘average’ male.

2.2 Clothing

During the experiments the subjects were wearing standard winter work clothing of the Royal Netherlands Air Force. This consisted of: thermal underwear, battle dress, warm overall, dickey, warm socks, work shoes, fur hat with ear flaps, leather gloves and 'trigger finger' mittens. Goggles were used to prevent freezing of the eyes. 'Camaches' were put around the ankles to prevent excessive air movement through the trousers. Every subject was exposed to cold with and without an additional parka. The thickness of the clothing parts was determined under a pressure of 100 Pa and these values were entered in the model of Lotens and Havenith (13) to determine the insulation values for a minimal wind speed. The insulation without a parka was 0.35 m^2K/W, the insulation with a parka was 0.38 m^2K/W.

2.3 Climatic conditions

Every subject participated in nine different sessions. The ambient temperature was set to 0, -10 en -20°C and the wind speeds to 0.2, 4 and 8 m/s (0.9, 14.4 and 28.8 km/h) (measured about one meter from the ground and about 20 cm in front of the face of the subject). The wind speed at the face was recalculated to wind speed at 10 m height by multiplication with a factor 1.5, as recommended in ISO 11079 (10). This leads to nine different WCET values (Table 1).

Table 1: Wind Chill Equivalent Temperature (WCET) values for the nine investigated thermal conditions

Wind speed (m/s)		Ambient temperature (°C)		
		0	-10	-20
at the face	at 10 m high			
0 - 0.5	0.4	1.2	-9.1	-19.4
3.5 - 4.5	6.0	-5.5	-18.1	-30.7
7.5 - 8.5	12.0	-7.7	-21.0	-34.4

2.4 Dexterity determination

Immediately after entering the cold room the subjects were asked to sit on a chair. For the wind speeds of 14.4 and 28.8 km/h the subject was seated in the wind tunnel. If the wind was minimal the subject was seated in a shielded part of the climatic chamber.

Three times, every twenty minutes the subjects performed the dexterity test, starting about one minute after entering the cold room. The Purdue pegboard test was shown to be well correlated to finger dexterity (14). In thirty seconds the subjects had to place as much pins in the board as possible with both hands. The gloves were removed during the test since those fine dexterity tasks can only be performed with bare hands.

Hereafter, the subjects had to indicate the cold sensation on a list ranging form 8 to -8 with the adjectives 'very hot' (8), 'hot' (6), 'uncomfortably warm' (4), 'comfortably warm' (2), 'neutral' (0), 'comfortably cool' (-2), 'uncomfortably cool' (-4), 'cold' (-6) and 'very cold' (-8).

During the periods that the subjects were not performing tasks in the cold room, they were sitting quietly with gloves and mittens over their hands. After the last test the subjects left the climatic chamber and stayed in a room of about 30°C for at least one hour to rewarm. The gloves, mittens, hat and parka were removed during the recovery period.

2.5 Temperature determination

The temperature of the left cheek bone (T_{ch}) and the ventral side of the distal phalanx of the left toe (T_{toe}) and left little finger (T_{fi}) was determined by a copper-constantane thermocouple. The sensor was fixed to the skin by 25 mm wide air permeable tape.

Rectal temperature (Tre) was continuously measured by a thermistor (YSI 701) inserted about 12 cm in the rectum.

Three thermocouples were placed on the body to estimate the mean skin temperature (Tsk): on the sternum (Tchest), the belly of the biceps brachii (Tarm) and the medial vastus muscle (Tleg). Tsk is calculated as (15):

0.36 Tarm + 0.25 Tchest + 0.34 Tleg + 1.19 [1]

This formula is validated against surface weighted calculation for 10 locations for a temperature range of 13 to 49°C and variable wind speed (15).

The mean body temperature (Tb) is calculated by a formula by Farnworth and Havenith (16):

Tb = 0.56 Tre + 0.02 Tchest + 0.04 Tfi + 0.065 Tarm + 0.145 Ttoe + 0.180 Tleg + 0.08 [2]

2.6 Termination of the experiment

The experiment was terminated when the subject or the experimenter indicated that the cold was no longer tolerable. Moreover, the experiment was terminated when rectal temperature was below 35°C or if one of the determined skin temperatures fell below 5°C. When the experiment was terminated, the subjects were removed from the cold immediately.

2.7 Statistics

The effect of clothing insulation on the determined variables was tested with a one-way MANOVA (17). This test is equal to a paired t-test.

The dexterity decrease in the cold was related to WCET and exposure duration. To determine the best relation, a curve was fitted with the general equation: dexterity decrease = a + b * WCET * duration^c. Fitting was performed using the Levenberg-Marquardt least squares method.

The reported temperatures are averaged over the 3 minutes preceding and 3 minutes following minute 10, 20, 30, 40 and 50.

3 RESULTS

Drop-outs

The total number of sessions was: 12 (subjects) x 9 (WCET) x 2 (clothing) = 216. Two sessions were missed due to absence of the subjects, leaving 214 for the analysis.

In all 214 sessions the subjects stayed in the climatic chamber for at least 20 minutes. Twelve sessions were ended before the 40th minute and 36 before minute 60. The dropouts were only found for low WCET-values. The percentage dropout thus was related to the combination of WCET and exposure duration. This is shown graphically in Fig.1. When WCET multiplied by exposure duration became less than 1300 °C·min, the number of dropouts rapidly increased. Almost all sessions were ended due to the toe temperature exclusion criterion.

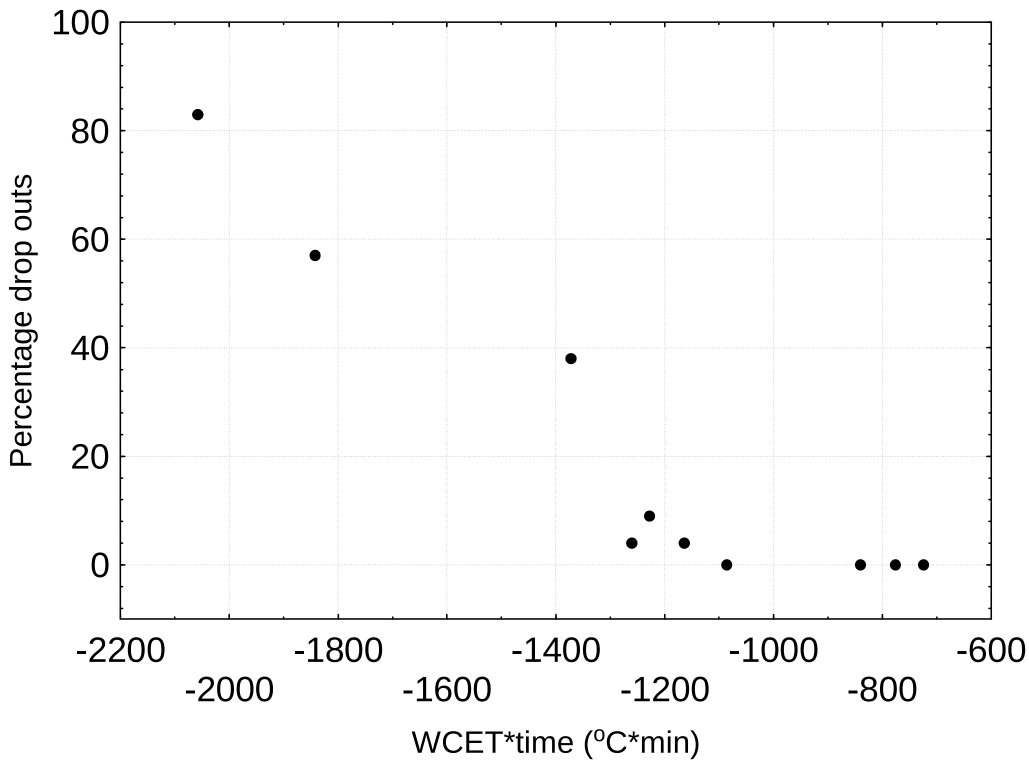

Figure 1: Percentage of dropouts related to the product of windchill equivalent temperature and exposure duration (in °C·min).

Clothing

There was no significant difference between the two clothing ensembles for T_{re} ($F(1,996)=0.0$, $P>0.05$), the Purdue Pegboard test ($F(1,808)=0.01$, $P>0.05$) and toe temperature ($F(1,1017)=2.7$, $P>0.05$). Wearing the parka was related to a higher T_{sk} of 32.0 ± 1.9 °C versus 30.7 ± 1.9 °C ($F(1,1007)=115.7$, $P<0.001$). All measured skin temperatures, except for the toe, were higher when the parka was worn.

Wearing the parka was accompanied by a significantly warmer feeling of –1.7 ± 3.0 versus –2.8 ± 2.8 ($F(1,802)=28.1$, $P<0.001$).

Direct effect of climatic factors on dexterity

Dexterity was strongly related to WCET and exposure duration. For the fitted curve dexterity decrease = a + b * WCET * duration^c, the c value equaled 0.48 for finger dexterity.

If we set the manual performance at the 0°C low wind condition to 0% we can estimate the dexterity decrease. We averaged the values over subjects, which leaves us with 72 data points (9 WCET * 4 exposure durations (0, 20, 40 and 60 minutes) * 2 clothing ensembles). The resulting regression equation is:

Finger dexterity decrease = 0.127 * WCET * duration$^{0.48}$ (r = 0.93[1]) [3]

Thus, for a WCET of -10°C and an exposure time of 30 minutes a decrease in finger dexterity of about 6% can be expected.

Effect of finger skin temperature on dexterity

The relation between T_{fi} and finger dexterity is shown in Fig. 2. At finger temperatures of less than about 14°C the performance decreases. The dropouts at low T_{fi} may even cause underestimation of the dexterity decrease at low temperatures.

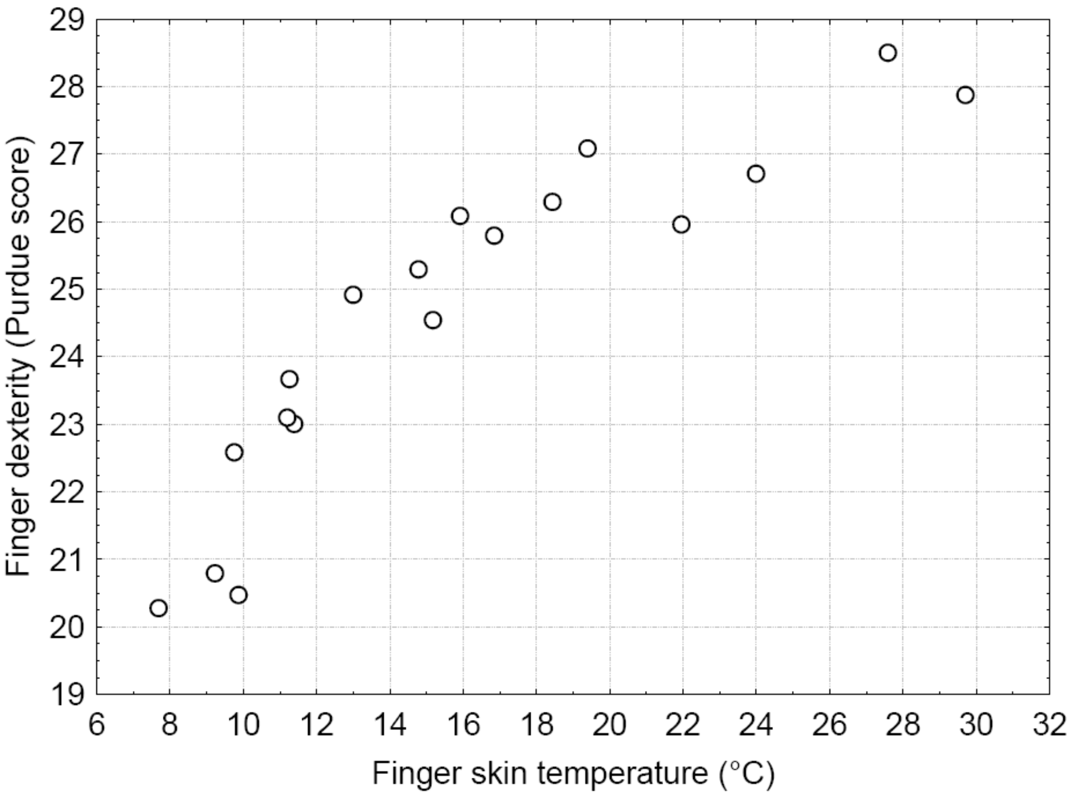

Figure 2: Relation between finger skin temperature (℃) and finger dexterity (Purdue pegboard score). T he values are averaged over twelve subjects and clothing insulation. Each point stands for a measurement with fixed windchill equivalent temperature after 20 or 40 minutes of exposure time.

There was a distinct relation between T_b and finger dexterity. The method of T_b-calculation by Farnworth and Havenith (16) showed a better correlation with finger dexterity (r = 0.92) than the traditional method weighing only rectal and mean skin temperature with appropriate weight factors for a cold body (0.6 T_{re} + 0.4 T_{sk}) (r = 0.89).

The fat percentage of the subjects had no relation with the scores on the finger dexterity tests.

[1] r = 0.48 including subject variability

4 DISCUSSION

The goal of the study was to relate finger dexterity to the WCET. It was shown that the combination of WCET and exposure duration was very well related to finger dexterity with a correlation of 0.93. Teichner (7) was one of the few who related dexterity to wind-chill. His subjects had to perform tasks after a 25-minute exposure to cold in well-insulated clothing and with gloves on. The finger dexterity tasks were performed without hand protection. If his results are recalculated to a WCET with a reference wind speed of 2 ms^{-1}, a performance decrease was found at WCET lower than -21°C. In our study, finger and hand dexterity decreased by 12% after exposure to -21°C WCET for 25 minutes. The finger temperature was just below 14°C in Teicher's study when serious dexterity decrement occurred. In Fig. 2 it is shown that also in our investigation finger dexterity decreased when finger temperature fell below 14°C.

Clark and Jones (18) showed that dexterity decreased during cold exposure, and that this decrease had a cold specific training effect. Subjects trained for their tasks in a cold environment performed better in the cold than subjects trained in a warm environment. In our investigation cold and wind were balanced, thereby excluding temperature specific training effects.

The experiment was performed with minimal workload: the only work performed was the displacement of the pins. In this situation performance decrease is expected to be maximal compared to situations in which humans are warmed by continuous exercise. So, the results can be interpreted as the worst condition. Moreover, in reality dexterity tasks are often performed in a situation in which exercise is minimal.

Clothing insulation had a strong influence on the subjective cold score and skin temperatures, but did not influence manual performance. The difference in insulation by the parka was about 0.38 m^2K/W (0.2 Clo), and probably insufficient to influence performance.

For the results to be useful in military operations, there is a need for percentages of dexterity decrease below which problems occur. This percentage is not easy to give since dexterity does not suddenly stop, but gradually decreases. However, if we take a finger skin temperature of 14°C as a threshold (see Fig. 2 and results of Teichner (7)) and relate this to the combination of WCET and exposure duration, we can make a curve of critical values (Figure 3). The formula corresponding to these values is:

$$0.0808 * WCET * duration^{0.48} = -9.136 \qquad [4]$$

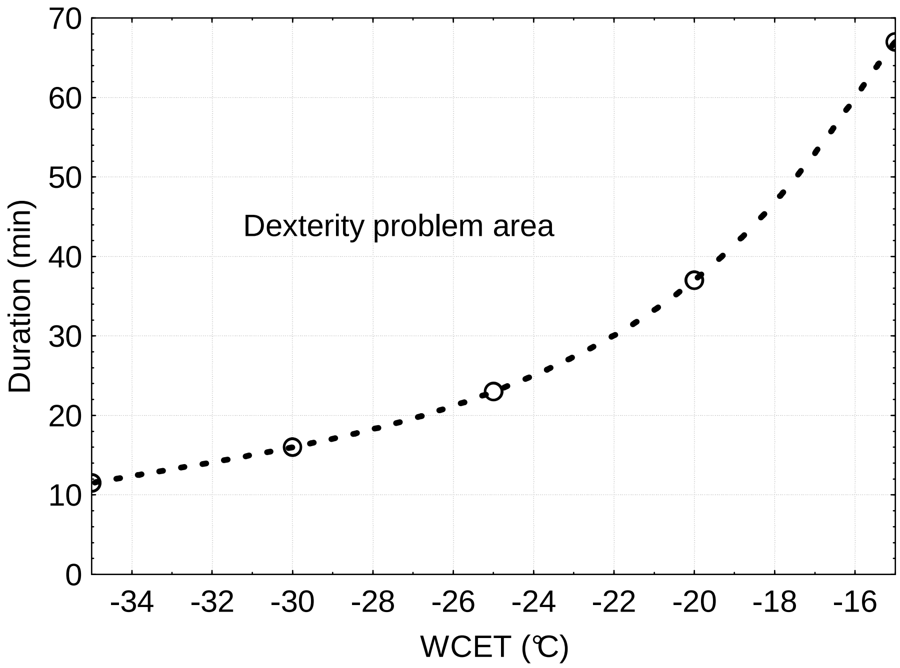

Figure 3: The left upper area in the figure indicates combinations of WCET (℃) and exposure durations for which the finger skin temperature will drop below -14℃ and dexterity problems may occur.

The dexterity decrease can mainly be attributed to reduced peripheral blood flow initiated by the drop in body temperature. However, previous work has shown that there is also a direct effect of cold on the synovial fluid in the fingers, causing reduced dexterity (19).

This study only reports the effect of wind and temperature on dexterity; other related factors as radiation and wetness of the hands are reported in the literature. Steadman (2) calculated the effects of full sunshine (135 Wm^2) on the WCET. For temperatures below 0°C the effect of sunshine is dependent on wind speed and almost independent on ambient temperature. For minimal wind speed about 7°C has to be added to the WCET, for a wind of 20 ms^{-1} about 3°C has to be added. Similar to solar radiation, the radiation to and from the subject is more important at low wind speeds. Shitzer (20) calculated that about 23% of heat loss can be attributed to ambient radiation at low wind speeds and about 5% at high wind speeds.

Another factor that influences the relation between dexterity and WCET is the presence of wet hands. Daanen (6) calculated that heat loss of continuously wet hands equals about twice the heat loss of dry hands in still air and three times in windy conditions. When a hand is not continuously wet, but only dipped in water once, about 7 kJ of heat is extracted from a hand.

This paper focuses on the finger dexterity only. Daanen (2009) also describes the effect of cold on hand dexterity and grip force.

In summary, we conclude that WCET in combination with exposure duration may serve as a good indicator for manual performance decrease in the WCET range of 1 to –34°C and exposure durations of up to one hour.

5 REFERENCES

(1) Müller R. (1982) Arbeit in Kälte - Insbisondere beim Löschen von Frost- und Frischfish (Work in the cold - In particular during unloading of frozen fish). Forschungsbericht 298 Bundesanstalt für Arbeitsschutz und Unfallforshung, Dortmund.

(2) Steadman RG (1984) A universal scale of apparent temperature. J Appl Meteor **23**,1674-87.

(3) Siple PA, Passel CF (1945) Measurements of dry atmospheric cooling in subfreezing temperatures. Proc Amer Phil Soc **89**,177-99.

(4) Terjung WH (1966) Physiological climates of conterminous United States: a bioclimatic classification based on man. Annals of the Association of American Geography **56,**141-79.

(5) Kunst AE, Groenhof F, Mackenbach JP (1994) The association between two windchill indices and daily mortality variation in the Netherlands. American Journal of Public Health **84,**1738-42.

(6) Daanen HAM (1993) Deterioration of manual performance in cold and windy climates. In: The Support of Air Operations under Extreme Hot and Cold Weather Conditions; Publication CP-540 of the Aerospace Medical Panel (AMP) of the Advisory Group for Aerospace Research and Developement (AGARD) of the North Atlantic Treaty Organisation (NATO). Victoria, Canada:15-1-15-10.

(7) Teichner WH (1957) Manual dexterity in the cold. Journal of Applied Physiology **11**,333-8.

(8) Steadman RG (1971) Indices of Windchill of Clothed Persons. J Appl Meteor **10**,674-83.

(9) Tikuisis P, Osczevski RJ (2003) Facial cooling during cold air exposure. Bulletin of the American Meteorological Society **84**,927-33.

(10) ISO 11079 (2007) Ergonomics of the thermal environment -- Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects. International Organization for Standardization, Geneva, Switzerland.

(11) Shitzer A (2006) Wind-chill-equivalent temperatures: Regarding the impact due to the variability of the environmental convective heat transfer coefficient. International Journal of Biometeorology **50**,224-32.

(12) Fox EL, Mathews DK (1981) The physiological basis of physical education and athletics. Saunders, Philadelphia, USA.

(13) Lotens WA, Havenith G (1991) Calculation of clothing insulation and vapour resistance. Ergonomics **34**,233-54.

(14) Fleishman EA, Ellison GD (1962) A factor analysis of fine manipulative tests. Journal of Applied Psychology **46**,96-105.

(15) Lund DD, Gisolfi CV (1974) Estimation of mean skin temperature during exercise. Journal of Applied Physiology **36**,626-8.

(16) Farnworth B, Havenith G (1987) Improved estimation of body heat distribution during cooling: a first attempt. Report TNO Human Factors Soesterberg, The Netherlands No 1987-38.

(17) StatSoft Inc (2008) STATISTICA (data analysis software system). version 8 0 www statsoft com.

(18) Clark RE, Jones CE (1962) Manual performance during cold exposure as a function of practice level and the thermal conditions of training. Journal of Applied Psychology **46**,276-80.

(19) Hunter J, Kerr EH, Whillans MG (1952) The relation between joint stiffness upon exposure to cold and the characteristics of synovial fluid. Canadian Journal of Medical Science **30**,367-77.

(20) Shitzer A (2007) Assessment of the effects of environmental radiation on wind chill equivalent temperatures. European Journal of Applied Physiology **104**,215-20.

(21) Daanen HAM (2009) Manual performance deterioration in the cold estimated using the wind-chill equivalent temperature. Accepted for publication in Industrial Health.