Manual Performance Deterioration in the Cold Estimated Using the Wind Chill Equivalent Temperature

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Abstract: Manual performance during work 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- and hand dexterity and grip force 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, hand dexterity by the Minnesota manual dexterity test and grip force by a hand dynamometer. 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 manual performance. The deterioration in manual performance appeared to be strongly dependent upon Wind Chill Equivalent Temperature (WCET) and the square root of exposure time (r=0.93 for group average). These simple models may be valuable to assess problems with work in the cold, but more work should be done to determine critical values in dexterity for a wide variety of operational tasks.

Key words: Dexterity, Cold, Manual performance, Wind-chill

Introduction

Decreased dexterity is a major problem for manual work during prolonged cold exposure. 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 crit-

ical 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' temper-

ature '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[10]:

$$WCET = 13.12 + 0.6215*T - 11.37*v^{0.16} + 0.3965*T*v^{0.16}$$

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 m 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.

In addition, the effect of WCET on body temperature will be quantified as well as the relation between body temperature and dexterity. We hypothesize that body temperature depends on WCET and that manual dexterity depends on body temperature. Thus, the body temperature serves as an important intermediate between WCET and dexterity.

Subjects and Methods

Subjects

Twelve healthy males, 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 relevant data of the subjects is shown in Table 1.

The subjects participating in the experiment were selected in such a way that their average fat percentage was just below average. The average fat percentage of the subjects was 13.5%. 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 brought about so that the resulting cold exposure times based on this population will be 'on the safe side' for the 'average' male that has a slightly higher fat percentage and will probably start moving around in the cold or do a warming-up prior to

Table 1. Data of the investigated subjects

nr	age	weight	height	BSA	fat	hand volume		hand surface area	
						L	R	L	R
	years	kg	cm	m²	%	cm³	cm³	cm²	cm²
1	37	68	174	1.82	15.1	475	455	164	167
2	24	63	181	1.81	6.6	480	476	181	178
3	21	76	197	2.08	11.0	440	468	169	174
4	32	85	188	2.11	19.4	510	537	183	181
5	20	70	184	1.92	7.7	515	520	195	195
6	23	94	188	2.21	17.7	514	505	180	176
7	39	65	171	1.76	19.2	415	420	152	150
8	28	76	185	1.99	12.8	478	495	166	173
9	26	85	187	2.10	19.8	480	520	179	185
10	21	56	173	1.67	11.6	360	365	141	142
11	25	94	195	2.26	13.4	520	552	187	200
12	24	75	183	1.96	7.5	440	447	169	164
Mean	27	76	184	1.97	13.5	469	480	172	174
SD	6	12	8	0.18	4.8	48	53	15	17

BSA=body surface area, L=left, R=right. Body surface area is calculated according to Dubois and Dubois[22]. The volumes and surfaces are not significantly different between the left and right hands (paired *t*-test, *p*>0.05).

manual task performance in the cold.

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.

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 2).

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.

Every twenty minutes the subjects performed three dexterity tests, starting about one minute after entering the cold room.

The tests were:

Table 2. Wind-chill equivalent temperatures in °C for the selected climatic conditions

		Ambient temperature (°C)		
Wind speed (km/h)		0	–10	–20
at the face	at 10 m high			
0.9	1.4	1.2	–9.1	–19.4
14.4	21.6	–5.5	–18.1	–30.7
28.8	43.2	–7.7	–21.0	–34.4

Please note that wind speed measured at the face is multiplied by 1.5 to estimate the wind speed at 10 m height.

1 Purdue Pegboard test. This 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.

2 Minnesota Rate of Manipulation-Placing test, well correlated to hand dexterity[14)]. In 45 s the subjects had to place as many blocks as possible in the holes with both hands. The subjects were wearing leather gloves.

3 Maximal grip force, determined by the Jamar Deluxe Hand Dynamometer, model 0030J4. The distance between the handlebars was fixed to 5 cm. The force was determined with the arm stretched. The subjects were wearing leather gloves and synthetic mittens.

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).

In addition, the experienced difficulty of the Minnesota test was asked for and rated on a nine-point scale with the texts 'very easy' (1), 'easy' (3), 'neutral' (5), 'difficult' (7) and 'very difficult' (9).

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.

Temperature determination

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

Rectal temperature (T_{re}) 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 (T_{sk}): on the sternum (T_{chest}), the belly of the biceps brachii (T_{arm}) and the medial vastus muscle (T_{leg}). T_{sk} is calculated as[15)]:

$$0.36\ T_{arm} + 0.25\ T_{chest} + 0.34\ T_{leg} + 1.19 \qquad [1]$$

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 (T_b) is calculated by a formula by Farnworth and Havenith[16)]:

$$T_b = 0.56\ T_{re} + 0.07\ T_{sk} + 0.04\ T_{fi} + 0.04\ T_{arm} + 0.145\ T_{toe} + 0.145\ T_{leg} \qquad [2]$$

Since T_{sk} is based on arm and leg temperature, the formula can also be rewritten as

$$T_b = 0.56\ T_{re} + 0.02\ T_{chest} + 0.04\ T_{fi} + 0.065\ T_{arm} + 0.145\ T_{toe} + 0.180\ T_{leg} + 0.08 \qquad [3]$$

Termination criteria

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.

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. Fitting was performed using the Levenberg-Marquardt least squares method.

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

Results

Drop-outs

The total number of sessions was: 12 (subjects) × 9 (WCET) × 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 min. 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 1,300°C·min, the number of dropouts rapidly increased. Almost all sessions were ended due to the toe temperature exclusion criterion.

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), the Minnesota test (F(1,806)=0.05, *p*>0.05), grip force (F(1,803)=0.03, *p*>0.05) and toe temperature (F(1,1017)=2.7, *p*>0.05).

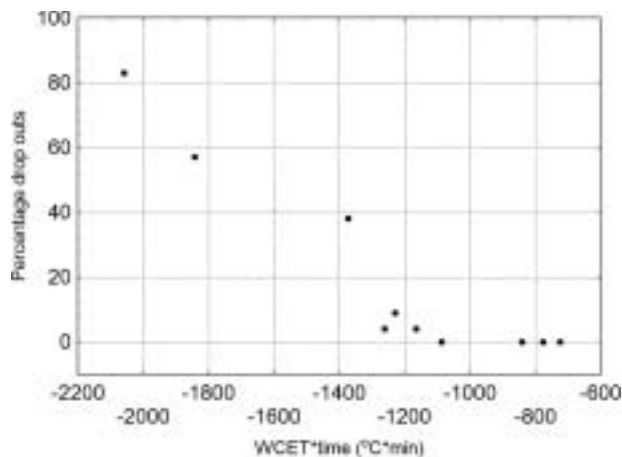Wearing the parka was accompanied by a significant-

Fig. 1. Percentage of dropouts related to the product of wind-chill equivalent temperature and exposure duration (in °C·min).

ly warmer feeling of -1.7 ± 3.0 versus -2.8 ± 2.8 (F(1,802)=28.1, *p*<0.001).

Wearing the parka was related to a higher T_{sk} of 32.0 ± 1.9 versus 30.7 ± 1.9 (F(1,1007)=115.7, *p*<0.001). All measured skin temperatures, except for the toe, were higher when the parka was worn.

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, the c value equaled 0.48 for Purdue, 0.38 for Minnesota and 0.25 for force determination, illustrating that exposure duration has most influence in fine dexterity tasks and less influence for force delivery.

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 min) * 2 clothing ensembles). The resulting regression equations are:

Finger dexterity decrease = 0.127 * WCET * duration^0.48 (r=0.93[1])   [4]

Manual dexterity decrease = 0.162 * WCET * duration^0.38 (r=0.88)   [5]

Grip force decrease = 0.141 * WCET * duration^0.25 (r=0.76)   [6]

Thus, for a WCET of -10°C and an exposure time of 30 min a decrease in dexterity of fingers and hands of about 6% can be expected, and about 3% force deterioration.

Mean skin and rectal temperature

Figure 2 shows the effect of ambient temperature, wind
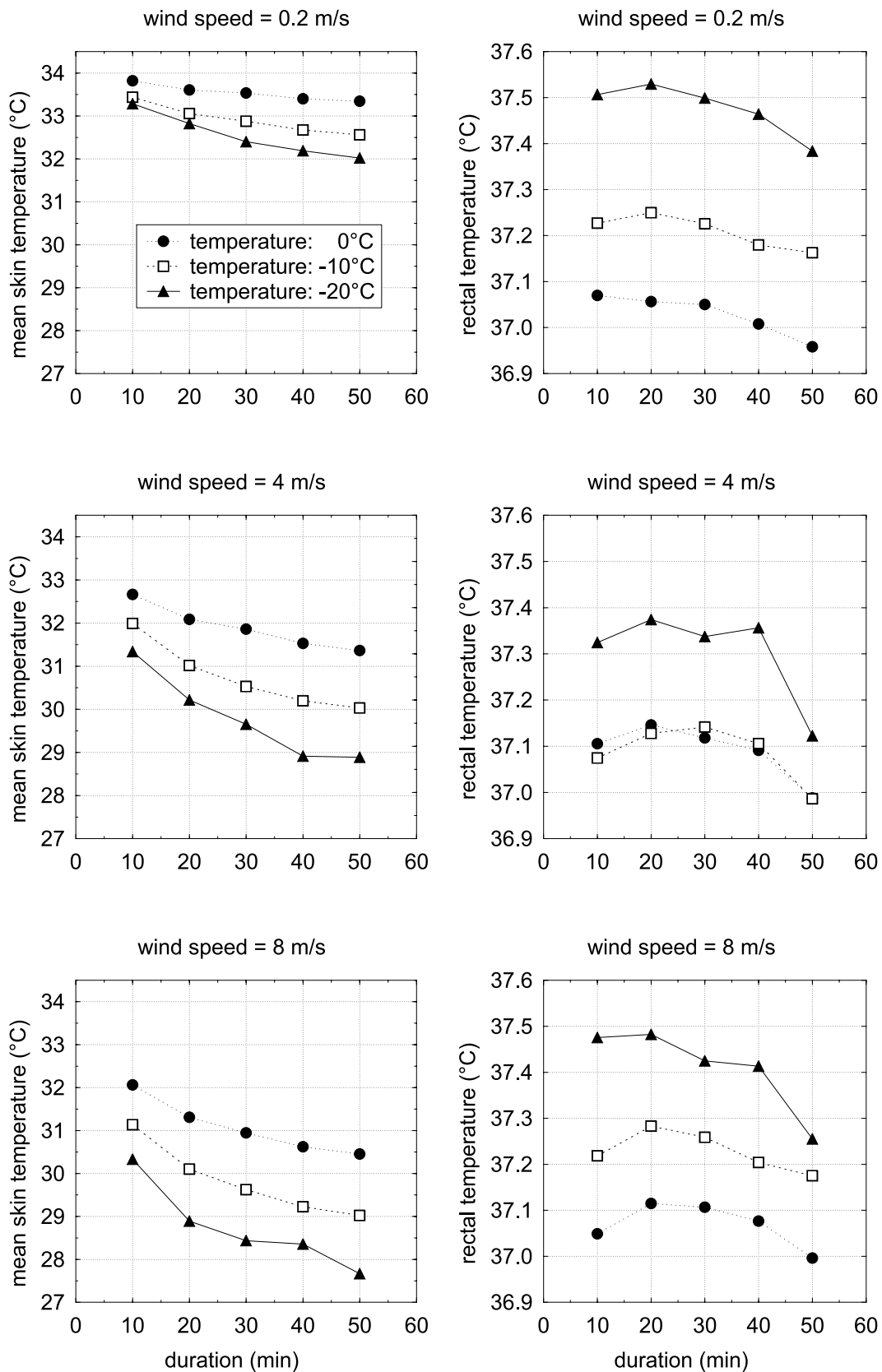
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[1] r=0.48 including subject variability

Fig. 2. Mean skin temperature in ˚C (left panels) and rectal temperature in ˚C (right panels) plotted against exposure duration in minutes for three wind speeds (0.2 m/s upper panels, 4 m/s middle panels and 8 m/s lower panels) and three ambient temperatures (0˚C closed circles, –10˚C open squares and –20˚C closed triangles) averaged over all subjects.
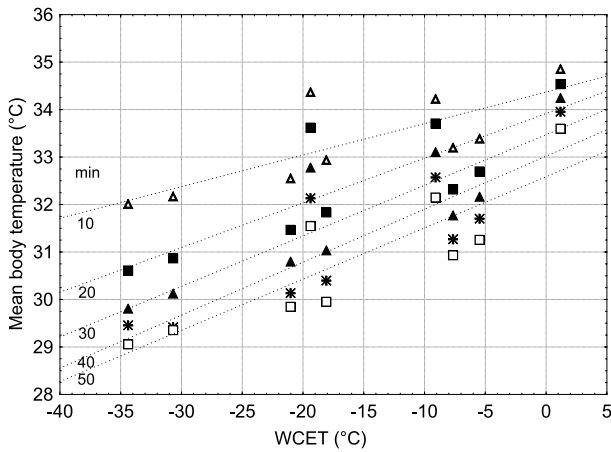
Fig. 3. Relation between windchill equivalent temperature (˚C) and mean body temperature (˚C) according to Farnworth and Havenith[16] for exposure times of 10, 20, 30, 40 and 50 min.
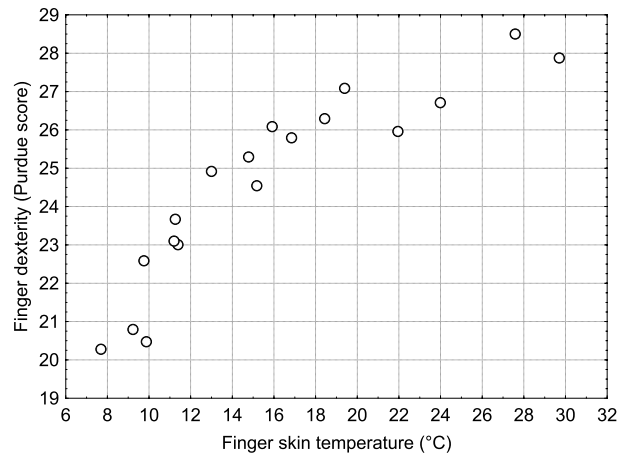

Fig. 4. Relation between finger skin temperature (˚C) and finger dexterity (Purdue pegboard score). The values are averaged over twelve subjects and clothing insulation. Each point stands for a measurement with fixed windchill equivalent temperature after 20 or 40 min of exposure time.

speed and exposure duration on mean skin temperature and rectal temperature.

Mean skin temperature dropped with increasing exposure duration, increasing wind speed and decreasing ambient temperature. Rectal temperature showed an increase during the initial minutes, probably due to the combined effects of vasoconstriction and increased thermogenesis and showed a decrease thereafter. Wind speed did not affect rectal temperature. Ambient temperature, however, showed an inverse effect on rectal temperature: when the ambient temperature was about 10˚C lower, the rectal temperature was about 0.2˚C higher.

Effect of climate on body temperature

T_b was very dependent upon WCET and exposure time (Fig. 3).

Effect of skin, rectal and body temperatures on dexterity

The performance on the tests and the subjective scores were related to T_{fi}, T_{re} and T_{sk}. The relation between T_{fi} and finger dexterity is shown in Fig. 4. At finger temperatures of less than 14˚C the performance decreases. The dropouts at low T_{toe} and T_{fi} may even cause underestimation of the dexterity decrease at low temperatures.

T_{fi} and T_{sk} are strongly related (r=0.91). Therefore, only T_{sk} is considered in the statistical analysis of Table 3. Dexterity is better for a high T_{sk} (and T_{fi}) and a low T_{re}. The subjective scores show an identical image to dexterity: the situation is assessed colder and more difficult when T_{sk} decreases and T_{re} increases.

There was a distinct relation between T_b and manual performance. In Table 4 the correlations are shown between T_b and performance. The method of T_b-calculation by Farnworth and Havenith[16] showed a better correlation with performance than the traditional method

Table 3. Regression equations of the test score related to rectal (T_{re}) and mean skin (T_{sk}) temperature

	Factor			
	Constant	T_{sk}	T_{re}	R
Finger dexterity	158.4	1.3	–4.6	0.98
Hand dexterity	215.1	1.7	–6.2	0.97
Hand grip force	364.7	0.8	–9.3	0.85
Cold sensation	60.9	1.3	–2.8	0.97
Experienced difficulty in hand dexterity task	–24.4	–0.4	1.1	0.96

r=multiple regression coefficient. Results are averaged over twelve subjects and two clothing insulation conditions (n=18: 9 windchill equivalent temperatures times two exposure durations (20 and 40 min)). The influence of every factor is significant ($p<0.05$).

Table 4. Correlation between mean body temperature calculated traditionally ($0.6 T_{re} + 0.4 T_{sk}$) and according to Farnworth and Havenith[16] and the test scores

	Method	
	$0.6 \cdot T_{re} + 0.4 \cdot T_{sk}$	(16)
Finger dexterity	0.89	0.92
Hand dexterity	0.88	0.89
Hand grip force	0.59	0.68
Cold sensation	0.92	0.96
Experienced difficulty in hand dexterity task	–0.90	–0.88

weighing only rectal and mean skin temperature with appropriate weight factors for a cold body ($0.6 T_{re} + 0.4 T_{sk}$).

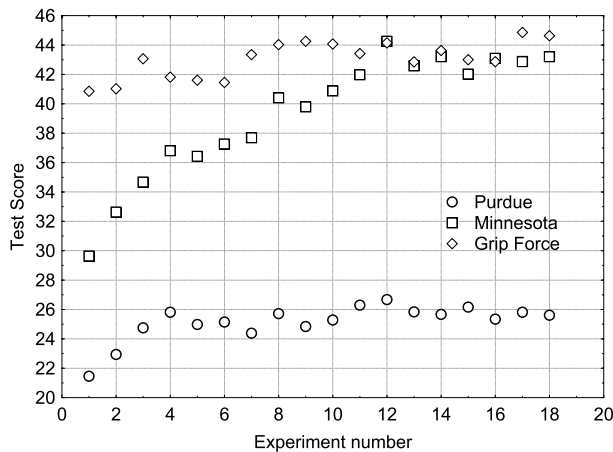The fat percentage of the subjects has no relation with

Fig. 5. Relation between experiment number and the absolute scores on the finger dexterity, hand dexterity and grip force test. Values are averaged over 12 subjects.

the scores on the finger and hand dexterity tests. Also the correlations of fat percentage with grip force, cold score and assessed difficulty were below 0.21.

Cold and difficulty assessment

The subjective cold score is lower for the least insulating clothing ensemble. The score is also dependent upon WCET and exposure time. The regression equation (based on 36 samples: 9 WCET * 2 durations * 2 clothing ensembles) is:

Cold score = –14.0 + 0.030 * WCET * duration$^{0.50}$ + 37.7 * I   (r=0.89)   [7]

In which I stands for Insulation in m^{2}K/W.

The subjective difficulty of the Minnesota test is not related to clothing insulation but only to WCET and exposure time. The regression equation (based on 18 samples: 9 WCET * 2 durations) is:

Difficulty = 2.93 – 0.018 * WCET * duration$^{0.37}$ (r=0.89)   [8]

Order effects

The design was balanced for ambient temperature, wind speed, clothing and time of day (morning, afternoon). Therefore, order effects are excluded. A data plot of the test performance against experiment number (Fig. 5) reveals that the balanced design was certainly needed because a learning curve is clearly present for finger dexterity and in particular hand dexterity.

Discussion

The goal of the study was to relate manual performance to the WCET. It was shown that the combination of

WCET and exposure duration was very well related to performance with correlations exceeding 0.9 for finger dexterity (formula [4]). Teichner[7] was one of the few who related dexterity to wind-chill. His subjects had to perform tasks after a 25-min 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 min. The finger temperature was just below 14°C in Teicher's study when serious dexterity decreases occurred. In Fig. 4 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 than subjects trained in a warm environment and then performing in the cold. 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 or blocks or one bout of maximal voluntary contraction. 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^{2}K/W (0.2 Clo), and probably insufficient to influence performance.

For the results to be useful in practical work situations, 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 decrements. However, if we take a finger skin temperature of 14°C as a threshold (see Fig. 4 and results of Teichner[7]) and relate this to the combination of WCET and exposure duration, we can make a table of critical values (Table 5). The formula corresponding to these values is:

0.0808 * WCET * duration$^{0.48}$ = –9.136   [9]

Not only the direct effect of temperature and wind on dexterity was investigated, but also the effect of temperature and wind on body temperatures. It was observed that the core temperature was higher when WCET was lower. This seems contradictory. Two possible expla-

Table 5. Combinations of WCET and exposure duration that correspond to estimated finger skin temperatures of 14°C

WCET (°C)	Exposure duration (min)
–10	>60
–20	37
–30	16
–40	9
–50	5

WCET values lower than the table values and exposure durations longer than the values in the table are expected to lead to considerable decrement in finger dexterity.

Table 6. Combinations of WCET and exposure duration that correspond to the cold sensations 'uncomfortably cool', 'cold' and 'very cold'

Uncomfortably cool		Cold		Very cold	
–10	>60	–10	>60	–10	>60
–20	52	–20	>60	–20	>60
–30	23	–30	49	–30	>60
–40	13	–40	27	–40	48
–50	8	–50	18	–50	31

nations are given below.

First, the low WCET might have caused a strong peripheral vasoconstriction, which cause peripheral circulation to be minimal thus preventing cold blood going to the body core. In combination with the enhanced metabolism, this might have caused the increased T_{re}.

Second, the subjects, knowing they were entering a cold environment, might have anticipated upon this by raising their activity level in the resting period. An analysis showed that this might indeed have been the case: the average T_{re} during the initial five minutes in the climatic chamber was 37.07 ± 0.09°C for WCET > -10°C and 37.30 ± 0.10°C for WCET < -20°C.

The good relation between WCET and body temperature on one hand and body temperature and dexterity on the other hand makes it likely to assume that the decrease of body temperature in the cold caused the dexterity decrease. 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 body temperatures, grip force and 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^2 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.

Dixon combined WCET isotherms with cold sensation scores[21], but used the Steadman index without reference wind. In this study we observed that the cold score is not only dependent on WCET, but also on exposure duration and clothing insulation (formula [7]). If we suppose that insulative clothing is worn (0.38 m^{2}K/W) Table 6 shows the WCET and duration values corresponding to the adjectives 'uncomfortably cool', 'cold' and 'very cold'.

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

The mean body temperature (T_b) can be considered as an important physiological intermediate between climatic conditions and manual performance. Dexterity tasks are well correlated with T_b, in particular when T_b calculations are not only based on T_{re} and T_{sk}, but on finger and toe temperatures as well. In line with previous observations, finger dexterity is severely impaired when the finger skin temperature drops below 14°C. Based on these observations, a table of critical values in WCET and exposure duration for finger dexterity is compiled for practical use.

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