Chapter 6*

Correspondence in the hunting reaction between the fingers of one cold immersed hand

6.1 Introduction

Immersion of an extremity in cold water leads to a fast decrease in temperature of the skin of the immersed body part. After some minutes, however, the temperature starts to increase again. This phenomenon is due to cold induced vasodilation (CIVD), and was first described by Lewis (1930). During the remaining immersion period the local skin temperature continues to fluctuate. Lewis called these fluctuations the hunting phenomenon. Studies of Grant and Bland (1931) showed that changes in blood flow through the arteriovenous anastomoses (AVA's) were probably responsible for the hunting reaction. This was confirmed later by several experiments (e.g., Fox and Wyatt, 1962). Hales (1985) states that "AVA's appear to have a high level of specificity as thermoregulatory effector organs".

Although the anatomical structures involved in CIVD are identified, the exact mechanism that causes CIVD is still unclear. Several theories are based on local mechanisms such as the release of a dilating substance (Aschoff, 1944), an axon reflex (Lewis, 1930) or local paralysis of smooth muscles in the vessel wall (Folkow et al., 1963; Vanggaard, 1975) (see par. 2.3.4). However, it has also been shown that core temperature plays a major role, because CIVD decreases in magnitude when the core becomes colder (see Table 2.1). The relative contribution of central and peripheral mechanisms to the hunting reaction is as yet not resolved.

A method to contribute to this discussion is to investigate the correspondence in hunting pattern between several cold-exposed fingers. A summary of results from different investigators is given in Table 6.1. According to Lewis (1930) one of the arguments in favour of central control is the concordance of the hunting pattern between two fingers immersed in cold water. In contrast, in the same article he also presented curves with hunting reactions with prevailing discordancy. In general, however, he noted that synchronization occurred. Synchronized hunting between fingers favours a central control hypothesis. Non-synchronized hunting favours peripheral control. The results shown in Table 6.1 were presented by the authors in a descriptive manner and were often based on typical results. It is the purpose of the experiments in this chapter, and the next two chapters to investigate the amount of correspondence quantitatively and thus contribute to the discussion on central and peripheral control.

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Table 6.1 Observations reported in the literature concerning synchronization in hunting reaction between fingers

Finger codes: 1 right thumb, 2 right index finger, 3 right middle finger, 4 right ring finger, 5 right little finger, 6 left thumb, 7 left index finger, 8 left middle finger, 9 left ring finger, 10 left little finger;
Water temp. water temperature in °C;
Imm. interval time between immersions in minutes;
? not mentioned.

Author(s)	# subjects	Fingers	Water temp.	Imm. interval	Results	Remarks
Greenfield et al., 1951a	11	2,7	0 - 6	5,10	no synchronization	heat loss measured
Lewis et al., 1930	?	2,7	0	0	generally synchronous	
Lewis et al., 1930	?	2,7	0	5	generally become synchronized	
Lewis et al., 1930	?	imm, n.imm	0	0	generally synchronized	
Kramer and Schulze, 1948	?	3 was cooled, 4 was control	air, 15 to -18	0	out of phase	
Hertzman and Roth, 1942	?	one cooled, one control	three methods	0	no synchronization	

The purpose of this investigation was to quantify a possible concordance in hunting reaction of the fingers of one immersed hand. Twelve subjects were asked to immerse the left hand in cold water. The temperature variations were measured at every finger tip and on the ventral and dorsal side of the hand. The hunting reactions of all locations were compared using the Pearson correlation coefficient (PCC) (see par. 3.11). A calorimeter measured the overall heat transfer of the hand to the water and this information was also used to estimate the amount of synchronization of the different fingers of the hand (see par. 3.11).

6.2 Materials and methods

subjects

Twelve healthy male subjects participated in the study. Their relevant anthropometric data are presented in Table 6.2.

Table 6.2. Anthropometric characteristics of the subjects.

subject	age	weight	stature	body surface area	palmar surface area	hand volume
	years	kg	cm	m^2	cm^2	cm^3
1	33	74	190	2.01	160	425
2	54	78	184	2.01	169	480
3	29	73	187	1.97	155	385
4	35	67	172	1.79	162	395
5	25	75	184	1.97	185	395
6	25	86	188	2.12	189	470
7	27	73	185	1.96	177	485
8	24	72	185	1.95	165	430
9	22	68	185	1.90	173	435
10	17	57	180	1.73	157	410
11	25	88	191	2.17	174	460
12	22	68	175	1.82	162	400
Mean	28	73	184	1.95	169	436
SD	9	8	6	0.13	11	35

methods

A copper-constantan thermocouple was placed on the distal phalanx of the thumb, index finger, middle finger, ring finger and little finger (see par. 3.3.1). Two other thermocouples, integrated in a heat flux sensor, were applied to the ventral and dorsal side of the hand (see par. 3.4).

The average hand skin temperature ($\bar{T}_h$) was calculated as follows:

$$\bar{T}_h = (T_{thumb} + T_{index\ finger} + T_{middle\ finger} + T_{ring\ finger} + T_{little\ finger} + 2.5 * T_{palm\ of\ the\ hand} + 2.5 * T_{back\ of\ the\ hand}) / 10 \quad [6.1]$$

The fingers were weighed equally and the dorsal and ventral sides of the hands were weighed 2.5 times the fingers. The latter roughly reflects the surface area distribution.

The heat transfer was determined by calorimetry as described in par. 3.5.

procedure
The experiments were carried out in a climatic chamber. The subjects had a rest period of about 20 minutes prior to immersion. The ambient temperature was 22°C and the relative humidity was 22%. The subjects were sitting on a chair with their left hand immersed in a calorimeter water bath of 4.2 to 5.8°C for 40 minutes.

data processing
The correspondence in hunting between the fingers was quantified by calculation of the Pearson correlation coefficients (PCC) and by relating the overall heat transfer, as measured by calorimetry, to the finger and hand temperature fluctuations.
The signals from the thermocouples, heat flux sensors and the thermopile and flow meter of the calorimeter were sampled every 16 seconds and the data was stored on a digital computer. The first 10 minutes after immersion were not included in the analysis, because the hand and finger temperatures are not dependent upon blood flow during this period (see par. 3.11).

6.3 Results

hunting reaction
In Fig. 6.1 the temperature fluctuations and the heat transfer to the water are shown for each subject.

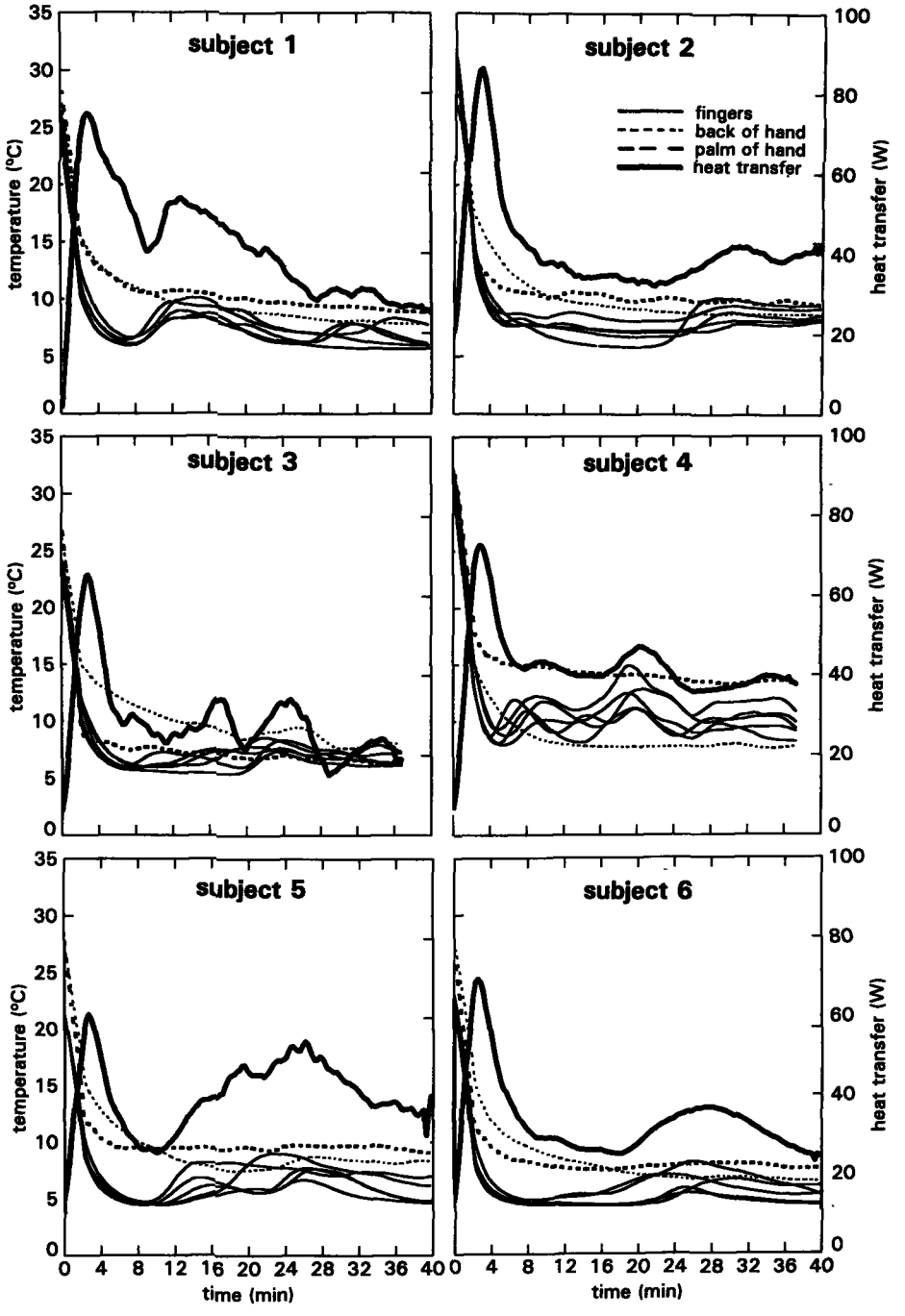

Fig. 6.1a Finger and hand temperatures (in °C) before and during immersion in water of about 5°C. The heat transfer of the hand to the water (in W) is shown by the thick solid line.

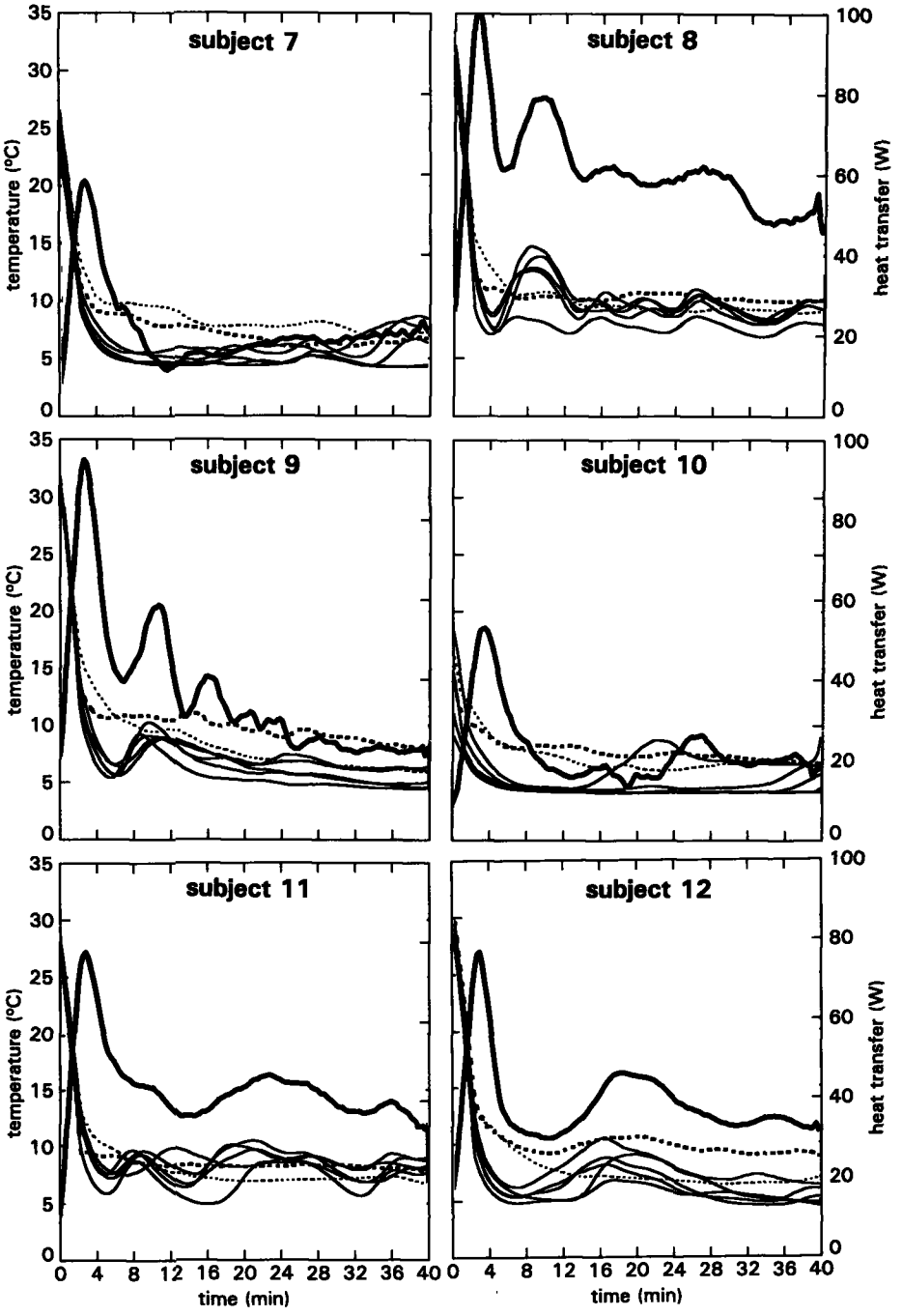

Fig. 6.1b Finger and hand temperatures (in °C) before and during immersion in water of about 5°C. The heat transfer of the hand to the water (in W) is shown by the thick solid line.

As can be seen in Fig. 6.1, the temperatures of the palm and back of the hand hardly showed fluctuations, contrary to the finger temperatures. The hunting reaction on the hand is small as compared to the fingers.

correspondence in hunting

The Pearson correlation coefficients (PCC's) between the temperature registrations are shown in Table 6.3 for every possible combination. The finger temperatures were related, especially those of neighbouring fingers. The larger the distance between the fingers the lower the PCC (Fig. 6.2). Neighbouring fingers had a mean PCC of 0.67 (n=48) versus 0.48 for the other fingers. This was significantly different ($p<0.01$, Kruskal-Wallis test). Correlations do not have a normal distribution. In this case, the skewness of the PCC of neighbouring fingers is -1.4, which means that the left tail of the frequency distribution was much longer than the right tail.

Table 6.3 Pearson correlation coefficients (PCC) averaged over 12 subjects for every combination of temperature registrations.

	thumb	index	middle	ring	little	palm	back
thumb	X						
index	0.42	X					
middle	0.46	0.83	X				
ring	0.30	0.63	0.68	X			
little	0.36	0.56	0.55	0.76	X		
palm	0.17	0.24	0.29	0.31	0.20	X	
back	-0.20	0.12	0.09	0.16	0.13	0.44	X

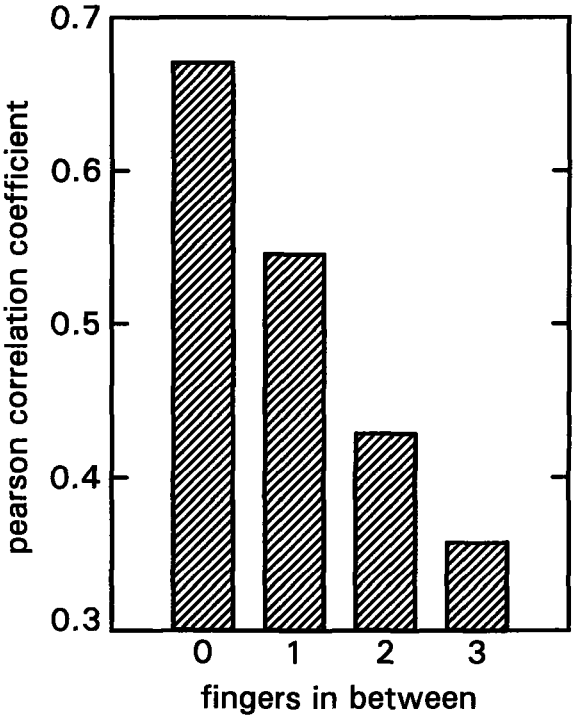

Fig. 6.2 Average Pearson correlation coefficients and SEM for fingers with 0 (n=48), 1 (n=36), 2 (n=24) or 3 (n=12) fingers in between.

Neighbouring fingers can be divided in two categories: those mainly innervated by the same nerves or mainly by different nerves. The highest correlations were found between the index and the middle finger (both mainly innervated by the median nerve, originating C7) and the ring and little finger (the little finger is completely innervated by the ulnar nerve and the ring finger partly, the ulnar nerve originates from C8). Those neighbouring fingers had a mean PCC of 0.79 (n=24) versus 0.55 (n=24) for the fingers with separate innervation. This was significantly different ($p<0.05$, Kruskal-Wallis test). The standard deviations were 0.17 and 0.41 respectively, but note that these values have to be interpreted with care, since the PCC-values are not normal distributed.

The calorimeter has a delayed response as compared to the temperature measurements. The time lag between heat transfer and average hand skin temperature ($\bar{T}_h$), determined by calculation of the time shift at which the maximal cross correlation coefficient (MCCC) occurs, was 161 ± 40 seconds. Therefore, the PCC of the calorimeter and the local skin temperatures may not be expected to be a good estimator of the amount of correspondence. The MCCC of the calorimeter and $\bar{T}_h$ was 0.82.

correspondence in hunting - calorimetric measurements

The water temperatures before and during immersion, hand and finger skin temperatures and heat transfer to the calorimeter bath are shown in Table 6.4. During the immersion the water temperature was about 0.4°C higher than before immersion. The palm of the hand had the highest mean temperature of all the measurement sites. The index finger was the warmest finger. The temperature of the fingers was lower on the ulnar side of the hand than on the radial side.

The magnitude of the hunting reaction is expressed as the coefficient of variation (CV) i.e. the SD within subjects divided by the mean. The smallest fluctuations are found for the palm and the back of the hand. The finger fluctuations are almost twice as high. The CV of the calorimeter is 31% of the mean CV of the fingers. If no correspondence would have occurred, the percentage should have been much lower; a perfect correspondence would have shown a higher percentage.

Table 6.4 Mean water temperature before and during immersion (°C), hand and finger skin temperatures (°C) and heat transfer (W) during the last 30 minutes of immersion in cold water. CV = Coefficient of Variation (SD within subjects / mean) averaged over 12 subjects. For the calculation of the CV of the hand and finger temperatures, the water temperature was subtracted in order to get a good baseline.

	mean	SD between subjects	SD within subjects	CV hunting
Water temperature before immersion (°C)	4.42	0.68	0.09	0.02
Water temperature during immersion (°C)	4.83	0.63	0.82	0.17
Hand palm temperature (°C)	9.19	1.95	1.01	0.11
Hand back temperature (°C)	7.97	0.95	1.35	0.17
Thumb temperature (°C)	7.54	1.21	2.94	0.39
Index finger temperature (°C)	7.64	1.89	3.29	0.43
Middle finger temperature (°C)	7.06	1.86	3.60	0.51
Ring finger temperature (°C)	6.88	1.84	3.30	0.48
Little finger temperature (°C)	6.56	1.89	4.00	0.61
Total heat transfer (W)	34.59	11.01	5.19	0.15

hunting parameters

Since the temperature fluctuations between the fingers are relatively well corresponding, Table 6.5 shows the hunting parameters for every subject, averaged over five fingers. Fig. 6.1 and Table 6.5 clearly show the large differences in hunting reaction between the investigated subjects.

Table 6.5 Hunting parameters with standard deviation between fingers for every investigated subject, averaged over five fingers. The water temperature during immersion (T_w) is shown as a reference. The standard deviation in T_w was always less than 0.1°C.

subject	T_{min} (°C)	T_{max} (°C)	Δt_{onset} (min)	Δt peak (min)	period (min)	T_w (°C)
1	6.3 ± 0.3	9.2 ± 0.7	8.1 ± 0.2	6.2 ± 1.6	13.2 ± 6.6	5.5
2	7.7 ± 1.1	8.7 ± 1.0	9.7 ± 6.4	3.7 ± 3.0	12.4 ± 4.9	5.8
3	5.9 ± 0.2	7.1 ± 1.2	10.2 ± 2.5	5.6 ± 4.1	12.2 ± 8.5	5.5
4	8.6 ± 0.6	11.5 ± 0.8	5.8 ± 0.7	3.8 ± 0.7	8.4 ± 1.0	5.8
5	4.5 ± 0.1	7.3 ± 1.3	10.4 ± 1.1	8.4 ± 2.5	16.7 ± 7.1	4.5
6	4.6 ± 0.2	5.3 ± 1.1	10.9 ± 3.1	8.2 ± 5.1	14.5 ± 10.5	4.3
7	4.9 ± 0.4	5.3 ± 0.6	12.6 ± 3.7	2.6 ± 1.5	5.4 ± 3.2	4.2
8	8.0 ± 0.8	12.7 ± 2.4	5.0 ± 0.2	4.1 ± 0.7	9.2 ± 0.7	4.8
9	6.0 ± 0.5	9.4 ± 0.6	7.0 ± 0.4	3.7 ± 0.6	13.1 ± 2.6	4.4
10	4.4 ± 0.1	5.2 ± 2.0	13.8 ± 1.1	4.6 ± 4.7	7.6 ± 7.7	4.2
11	7.2 ± 0.7	9.5 ± 0.4	6.4 ± 0.9	3.7 ± 0.8	10.0 ± 1.7	4.3
12	5.5 ± 0.5	8.8 ± 1.3	8.9 ± 2.5	9.4 ± 1.2	23.9 ± 6.2	4.5
Mean	6.1 ± 0.5	8.3 ± 1.1	9.0 ± 1.9	5.3 ± 2.2	12.2 ± 5.1	4.8
SD between subjects	1.4	2.3	2.6	2.2	4.6	0.6

6.4 Discussion

correspondence in hunting

Burton and Edholm (1955) observed that CIVD started at different times in the fingers of one hand, but that the onset time was rather similar when the fingers were immersed simultaneously. In this study the CIVD in the fingers started about 9.0 minutes after immersion and the standard deviation in this time was 1.9 minutes. In two subjects (1 and 8) the increase in finger temperatures started at the same time (SD of only 12 seconds), in others there was more variation. Therefore, the degree of correspondence differs between subjects (see onset time in table 6.5).

For neighbouring fingers, mainly innervated by the same nerve, the mean PCC of 0.79 indicates a high degree of correspondence between the hunting reactions of both fingers. For non-neighbouring fingers, such as the thumb and little finger, the amount of correspondence was much lower. See chapter 13 (general discussion) for an in depth discussion of the innervation of the fingers. The hand palm and hand back showed almost no hunting reaction and these temperature fluctuations were not related to those of the fingers. Therefore, the degree of correspondence is dependent upon the measured finger combination, and is higher for neighbouring fingers than for fingers far apart, such as the thumb and little finger.

The temperature fluctuations in the fingers and hand are reflected in the overall heat transfer, as determined by calorimetry. The heat transfer fluctuations were about 31% of the finger temperature fluctuations.

Our results show that the number of fluctuations in finger temperature was about 2 - 6 per hour. Lewis (1930) found the same range. This means that during our 30 minutes recording period at least one full hunting period was observed and therefore it is to be expected that differences in hunting pattern between the fingers were sufficiently quantified.

comparison of the results with hypothesized mechanisms

Our results show that considerable correspondence exists in hunting reaction between the fingers, especially for neighbouring fingers. Hypotheses focussing only on peripheral processes, such as the axon reflex, paralysis of the muscular vessel wall or an altered sensitivity of the norepinephrine receptors due to cold (see par. 2.3.4), can not explain the similarity in hunting reaction between neighbouring finger tips. Based on these hypotheses, the coldest finger should be the first one to initiate a hunting reaction, independently of the others. This study shows that this is not the case. In subject 4, for instance, in Fig. 6.1, a relative warm finger is the first to start hunting. Also, the hypothesis that a dilation substance enters the blood does not explain the correspondence between neighbouring fingers, unless the dilating agent is allowed to move to neighbouring fingertips, which is unlikely.

On the other hand, an exclusively central control is also unlikely because the correlation between non-neighbouring fingers is rather low (PCC = 0.36 for thumb and little finger).
Although an axon reflex is limited to a small area (Wårdell et al., 1993), it is possible that the antidromic conduction partially extends to the hand and may inhibit sympathetic activity to neighbouring fingers. This may explain the high PCC found for fingers sharing the same somatic nerves (PCC = 0.80). Another possibility is that the increased blood flow to the vasodilating finger skin increases the tissue temperature of that finger and also of the tissue surrounding the artery in the hand. The conduction of tissue heat may cause an artery to a neighbouring finger to open up. A favouring factor for this is that the hand arteries have many anastomoses.

differences between hand and finger skin temperatures
The temperature fluctuations were relatively small on the back of the hand (Table 6.4). On this site AVA's are almost absent (Fox and Wyatt, 1962), and the blood vessels in the skin of the back of the hand are less important for thermoregulatory control than vessels in the palm of the hand. For every subject a passive heat elimination takes place at this site during the cooling phase, resulting in a small standard deviation of the averaged temperature.
The mean finger skin temperature during immersion was lower for the fingers on the ulnar side of the hand as compared to the radial side. This was also found by Yoshimura and Iida (1952). This might imply that fingers on the ulnar side have a higher risk for freezing injuries than fingers on the radial side.

fluctuations in temperature during immersion
The coefficient of variation (CV) of the temperature at the palm and back of the hand was smaller than of the fingers. With the exception of the nail bed, most AVA's are found in the skin of the volar side of the distal phalanx (Grant and Bland, 1931). Here, the hunting reaction is expected to be maximal, leading to maximal temperature fluctuations. This was indeed the case in our results. The fluctuations at the palm of the hand are expected to be greater than at the back of the hand because more AVA's are present at this site. This was not the case, however. At the dorsal side of the hand the possibility exists that the sensor was placed in close vicinity of a superficial vein, which is hard to avoid. It is known that the blood coming from the AVA's prefers a superficial over a deep venous return (Vanggaard, 1975). Therefore, sensors placed over a vein on the back of the hand may have reflected the hunting phenomenon from the fingers or volar side of the hand.

The mean skin temperature of the hand ($\bar{T}_h$) shows a good agreement with the calorimetric results when shifted in time by 161 seconds (MCCC = 0.82). This delay of the calorimeter is caused by the time needed for the convection and conduction of heat from the hand to the thermopile at the boundary of the calorimeter. The delay is close to the calculated value of 140 sec (par. 3.5).

core temperature

In this investigation the core temperature was not determined, but it is rather likely that general body cooling occurred during the investigation. The low water bath temperature led to a heat loss of 35 W through the cooled hand during the last 30 minutes, which was probably not compensated for by the relatively low environmental temperature of 22°C. A decrease in core temperature is known to decrease the CIVD response (see Table 2.1).

6.5 Summary

The mechanism responsible for cold induced vasodilation (CIVD) is still subject to debate. Several theories are based on local mechanisms such as the release of a dilating substance, an axon reflex or local paralysis of smooth muscles in the vessel wall. However, it is also shown that core temperature has to play a major role, because CIVD decreases in magnitude when the core gets colder.
In this investigation, the interplay between local and central influence on the hunting reaction was investigated by taking a closer look at the amount of correspondence between the hunting patterns of the fingers tips in a cold exposed hand. A good correspondence supports a relatively great central influence; a low correspondence is in favour of peripheral influence.
Therefore, twelve subjects immersed their left hands in a calorimeter water bath of about 5°C. PCC's were calculated of all fingers and of the ventral and dorsal side of the hand. A period of 30 minutes was analysed, starting 10 minutes after immersion.
In this study the temperature fluctuations of the fingers had a relatively high amount of correspondence. The amount of correspondence differed between subjects and finger combinations. The PCC was higher for neighbouring fingers (PCC = 0.67) than for fingers separated by other fingers (PCC = 0.48). Nervous or vascular connections in the hand or arm must account for this. For neighbouring fingers those mainly innervated by the same somatic nerve (ring-little and index-middle finger) had a higher PCC (PCC = 0.79) than for the fingers with more separate innervation (PCC = 0.55). The PCC between the two locations on the hands and the fingers were insignificant.

Chapter 7*

Synchronization of the hunting reaction in the fingers of two cold immersed hands

7.1 Introduction

In the previous chapter the hunting reaction of the fingers of an immersed hand was compared. The amount of correspondence between fingers was estimated by the Pearson Correlation Coefficient (PCC). The amount of correspondence was generally high and it was shown that the PCC of neighbouring fingers of a hand immersed in water at about 5°C was much higher than fingers who were far apart. This implies that CIVD can not be regarded as a purely local phenomenon. Moreover, neighbouring fingers sharing the same somatic nerves showed a higher PCC than those with different innervation. From these results it was concluded that a nervous component may play a role in the hunting reaction.

Burton and Edholm (1955) observed that CIVD started at different times in the fingers when they were immersed non-simultaneously. This indicates that the opening of the blood vessels must have been independent of the central sympathetic activity, which is supposed to affect every finger of a hand in a similar way (Guyton and Hall, 1996). To test if the observation of Burton and Edholm (1955) could be confirmed quantitatively in a group of subjects, eight subjects were asked to immerse their two hands in cold water simultaneously or five minutes apart. If synchronization of the finger temperature profiles of different hands occurs, a central component has to be present which overrides the autonomous rhythm of each finger. The PCC of the finger temperature profiles was used as an estimator of the amount of correspondence and the occurrence of synchronization.

With this experimental set-up, the effect of geometry of the fingers on the hunting reaction can also be investigated. Due to similarities in vascularisation between identical fingers of each hand, the hunting frequencies of concomitant fingers may be more alike than those of different fingers.

7.2 Materials and Methods

subjects

Eight male subjects participated in the study. Their relevant anthropometric data are presented in Table 7.1.

* This study has been published as TNO report IZF 1992 B-11.

Table 7.1 Anthropometric characteristics of the subjects.

subject	age	weight	stature	body surface area	palmar surface area		hand volume	
	years	kg	cm	m^2	cm^2		cm^3	
					left	right	left	right
1	24	67	183	1.87	181	178	480	476
2	36	67	172	1.79	164	167	475	455
3	25	83	182	2.04	150	150	460	470
4	25	74	180	1.93	157	159	520	520
5	21	75	198	2.08	195	185	560	545
6	39	63	171	1.74	152	150	415	420
7	27	75	184	1.97	166	173	478	495
8	20	70	186	1.93	176	177	450	440
mean	27	72	182	1.92	167	167	480	478
SD	6	6	8	0.11	15	12	41	39

methods

The temperatures on the palmar side of the distal phalanx of the left and right index fingers and of the left middle finger were measured by a heat flux sensor with integrated thermocouple (see par. 3.4). The other 7 distal phalanx of the fingers were measured by copper-constantan thermocouples (see par. 3.3.1).

The rectal temperature of the subjects was measured by a thermolinear probe (YSI 701) inserted 120 mm beyond the rectal sphincter (par. 3.3.3). It was decided not to determine esophageal temperatures in this study, since this is experienced as more uncomfortable by the subjects. The goal to achieve a relatively stable core temperature can also be checked by the more slowly reacting rectal temperature.

The heat transfer of the immersed hand(s) was determined by calorimetry (par. 3.5). The calorimeter water flow was about 1.4 $l \cdot min^{-1}$ and checked on the visual display throughout the experiments.

The signals from the thermocouples and thermopile of the calorimeter were sampled every 16 seconds.

The initial 10 minutes of immersion were removed from the data set because during these minutes the finger skin temperature is not only dependent upon blood flow.

The finger skin temperature, heat transfer and water temperature were averaged over the immersion period after this 10th minute period. Differences between subjects, simultaneous (S) / non-simultaneous immersion (NS) and left / right hand were tested with an ANOVA. The interaction term subjects*left/right was included in the analysis.
In order to quantify the amount of synchronization, a computer algorithm calculated the time at which the minimal temperatures occurred, according to the method described in par. 3.3.1. A minimum temperature denotes the start of a vasodilation period. The analysis period was limited to minute 5 through 45. No more than four minima were calculated for each finger temperature registration. Next, the minima of the finger temperatures were compared to the minima of the other fingers. When all minima of two compared finger temperature registrations were within the same minute, both registrations were considered 100% synchronous. If only one out of four minima was in the same minute, the synchronicity was 25%.
The coefficient of variation (CV) was calculated for skin and water temperature, and heat transfer (see par. 3.11). This parameter indicates the amount of fluctuation and can be seen as an estimate for the magnitude of the hunting reaction. Differences in CV between subjects, S/NS and left/right were tested with an ANOVA.

procedure
The experiments were carried out in a climatic chamber. The ambient temperature (T_a) was 31°C with a relative humidity (RH) of 52%. Subjects were dressed in shorts and a T-shirt and were wearing socks and shoes. Every subject came to the laboratory on two consecutive days on the same time of day. The subjects had a rest period of about 20 minutes prior to immersion. They were sitting in front of the calorimeter in which both hands were immersed simultaneously (S), or 5 minutes in between (NS) (Table 7.2). The hands were hanging down during immersion in water of about 10°C. The lower arms were pronated, so that the back of both hands faced each other. The fingers were spread. A small layer of foam was inserted between the backs of both hands, but sometimes contact could not be prevented. The chest was supported by the back of a chair.

Table 7.2 Immersion order.

subject	day of appearance	hand to be immersed first
1	1	both
	2	left
2	1	left
	2	both
3	1	both
	2	right
4	1	right
	2	both
5	1	both
	2	right
6	1	right
	2	both
7	1	both
	2	left
8	1	left
	2	both

The hands stayed in the calorimeter for at least 47 minutes after the immersion of the last hand. During the immersion period the rectal temperature was controlled by heat radiation on the back of the body. As soon as a decrease in rectal temperature was seen, the amount of radiation was increased. Strong radiators were placed about two metres from the subjects back and the radiative heat was measured at the back by a Hund UDRM heat flux meter. The back of the subject was covered with a white towel, when radiation was applied.

7.3 Results

synchronization

In Fig. 7.1 the hunting reactions of the middle fingers of the left and right hand are shown for each subject as well as the heat transfer of the hand in the non-simultaneous (left window) and simultaneous (right window) immersion conditions. The middle finger response is representative for the response of the other immersed fingers.

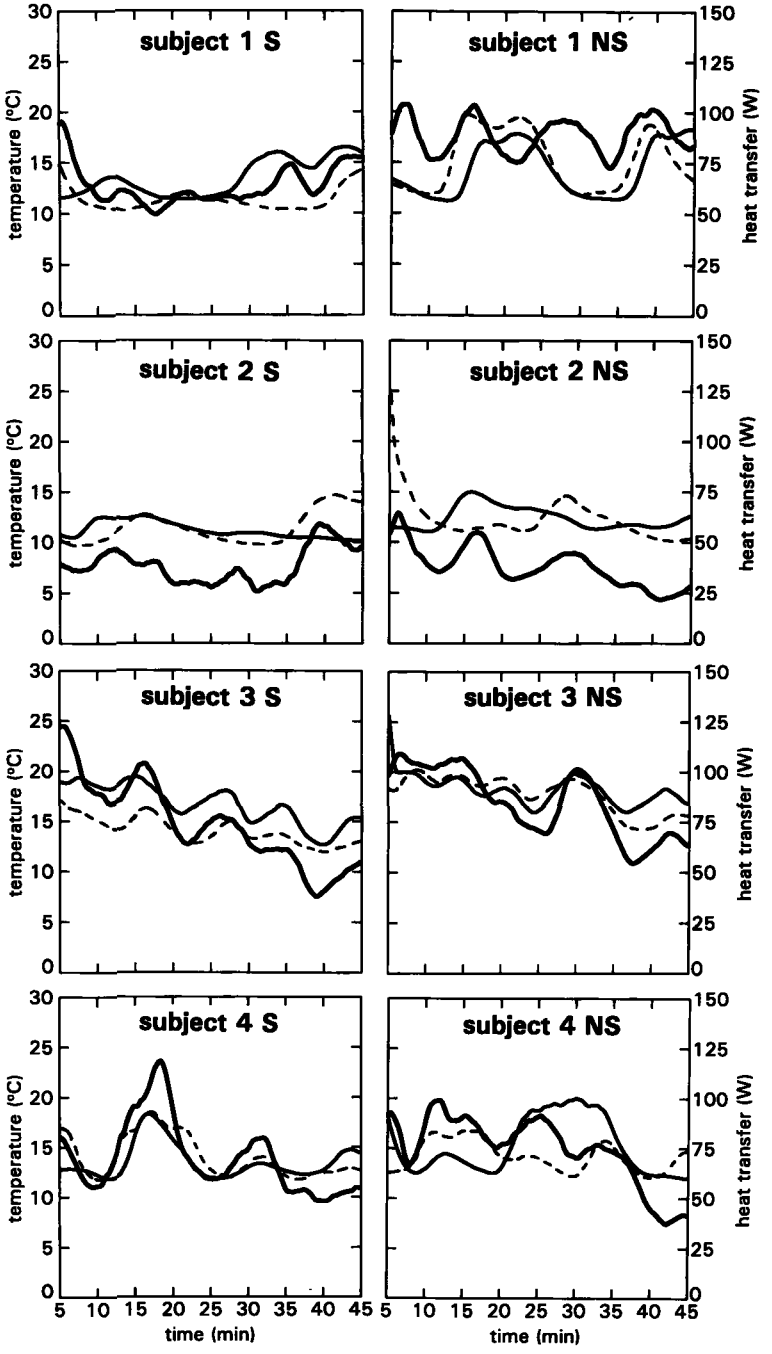

Fig. 7.1a Middle finger skin temperatures (in °C) of the left and right hand during the 5th to 45th minute of immersion for each subject. The total heat transfer of both hands to the water (in W) is shown by the thick solid line. The left window denotes simultaneous immersion; the right window denotes non-simultaneous immersion.

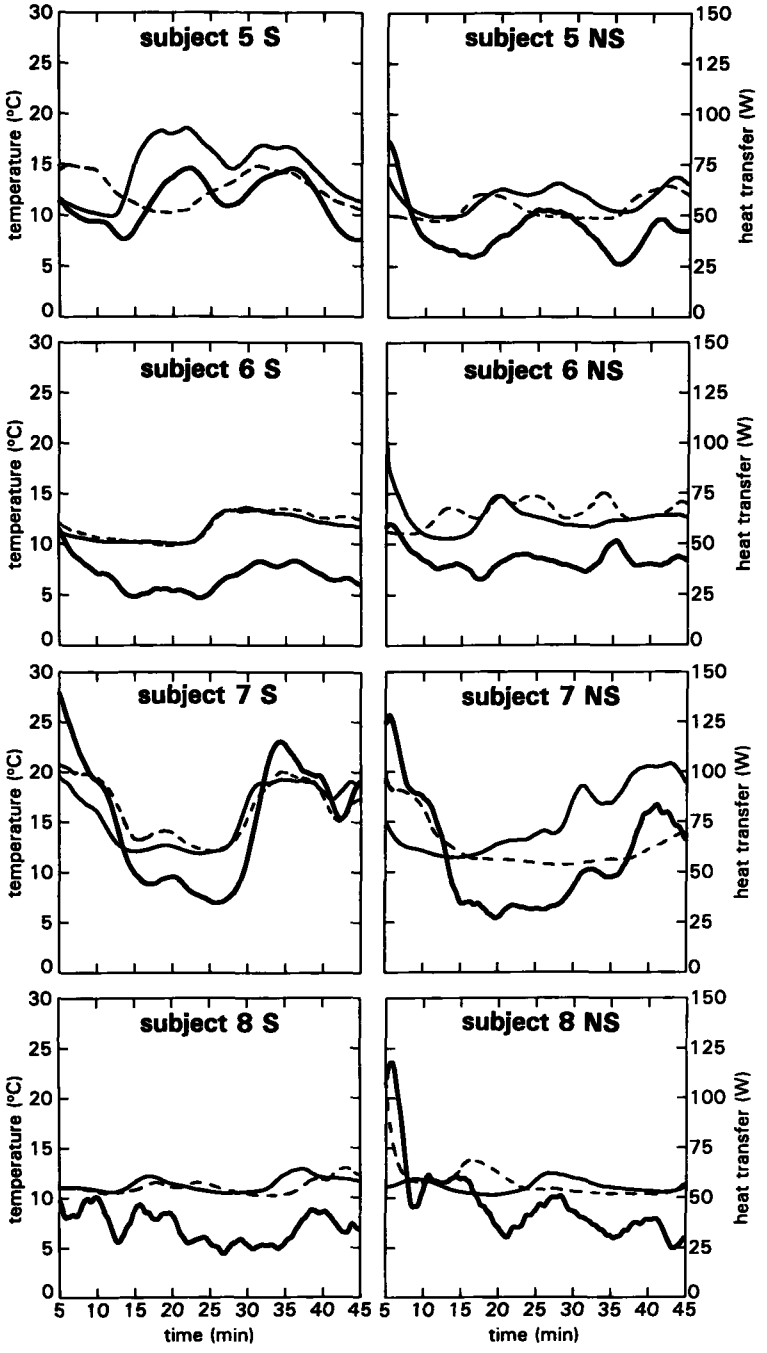

Fig. 7.1b Middle finger skin temperatures (in °C) of the left and right hand during the 5th to 45th minute of immersion for each subject. The total heat transfer of both hands to the water (in W) is shown by the thick solid line. The left window denotes simultaneous immersion; the right window denotes non-simultaneous immersion.

Fig. 7.1 illustrates the large variability in hunting reactions between subjects. Subject 3, for instance, shows a considerable amount of synchronization for both the simultaneous (S) and non-simultaneous (NS) condition. Subject 8, on the other hand, hardly shows any synchronization for both conditions. Subject 4 shows synchronization for the S condition, but not for the NS condition.

In Table 7.3 the amount of synchronization is shown for each subject in the S and NS condition in the same hand and between the two hands. A value of 12 means that the starting times of CIVD were identical in 12 percent of the cases. The average SD of the values is 27.5. A relatively high amount of synchronization, as in subject 3 NS and subject 7 S, can clearly be identified in Fig. 7.1 as similar hunting curves for the left and right hand.

Table 7.3 Synchronization of CIVD. The frequency of synchronous hunting reactions (%) is shown for each subject for the simultaneous and non-simultaneous immersion condition between fingers of the same hand and of different hands. The SD in the lowest row is the mean SD within subjects.

subject	simultaneous immersion		non-simultaneous immersion	
	in hands	between hands	in hands	between hands
1	12	14	23	15
2	19	16	23	24
3	20	23	36	31
4	25	23	19	5
5	14	16	15	13
6	24	15	22	13
7	36	27	23	5
8	20	24	15	9
mean	21	20	22	14
SD	30	28	32	25

Analysis of variance showed that there are no differences in synchronization between the simultaneous and non-simultaneous immersion. The amount of synchronization was greater within the same hand than between hands ($p<0.05$), in particular when the hands were immersed non-synchronously (interaction significant, $p<0.05$).

finger skin temperatures

In Table 7.4 the resulting finger skin temperatures are shown for every experimental situation, as well as the heat transfer and water temperature. There was no difference in finger temperature between the simultaneous and non-simultaneous immersion. Differences between the right and left hand were only found for the little finger. Subject differences were significant for all skin temperatures.

Table 7.4 Mean finger skin temperature (°C), mean heat transfer (W) and mean water temperature (°C) ± SD between subjects starting 10 minutes after immersion of the last hand in cold water to minute 45.

	simultaneous immersion		non-simultaneous immersion	
	left	right	left	right
thumb (°C)	13.7 ± 2.6	13.5 ± 1.9	13.7 ± 2.5	13.0± 2.1
index (°C)	13.6 ± 2.0	13.0 ± 1.4	14.0 ± 2.1	12.9± 1.9
middle (°C)	13.4 ± 2.1	14.4 ± 2.0	13.8 ± 2.2	13.4± 2.1
ring (°C)	13.2 ± 2.5	13.1 ± 1.9	13.5 ± 2.8	12.4± 1.7
little (°C)	13.1 ± 2.1	12.6 ± 1.7	13.3 ± 1.9	12.1± 1.6
heat transfer (W)	52.4 ± 15.9		52.0 ± 13.8	
water temperature (°C)	10.0 ± 0.4		10.0 ± 0.4	

fluctuations in heat transfer and finger skin temperature

In Table 7.5 the coefficient of variation (CV) of local skin temperature and heat transfer is shown for every experiment. The CV for skin temperature showed significant inter subject differences for the thumb and index finger only. There was no difference between the simultaneous and non-simultaneous immersion and left/right. The CV of the calorimeter was 43% of the CV of the average finger skin temperatures. The water temperature was relatively constant. This means that the cooling capacity of the calorimeter was sufficient.

Table 7.5 Coefficient of Variation (CV) of the local skin temperature (°C), heat transfer (W) and water temperature (°C) starting 10 minutes after the immersion of the last hand in cold water. For the calculation of the CV of the finger temperatures the water temperature was subtracted in order to get a zero base.

	simultaneous immersion		non-simultaneous	
	left	right	left	right
thumb (°C)	0.50	0.46	0.52	0.39
index finger (°C)	0.47	0.54	0.44	0.53
middle finger (°C)	0.54	0.49	0.53	0.51
ring finger (°C)	0.60	0.46	0.55	0.57
little finger (°C)	0.48	0.62	0.52	0.89
heat transfer (W)	0.23		0.23	
water temperature (°C)	0.02		0.02	

correspondence

In Table 7.6 the mean Pearson Correlation Coefficient (PCC) for simultaneous and non-simultaneous immersion is shown for every subject for the same hand and the other hand. There was no difference in mean PCC of all the fingers between the simultaneous and non-simultaneous immersion (Kruskal-Wallis one way analysis of variance by ranks, $n = 360$, $p > 0.05$). The PCC's were higher within a hand than between hands ($n = 320$ for the same hand and $n = 400$ between hands, $p < 0.001$). The PCC for similar fingers of the other hand (e.g., left index finger as compared to right index finger) was not higher than for different fingers ($p > 0.05$). The PCC's were respectively 0.45 ± 0.45 ($n = 80$) for similar fingers and 0.39 ± 0.47 ($n = 320$) for different fingers of the other hand.

Table 7.6 Mean Pearson Correlation Coefficients (PCC) for all subjects for simultaneous and non-simultaneous immersion. The PCC's are calculated within one hand (n=20 for every cell) and between two hands (n=25 for every cell).

sub-ject	simultaneous immersion				non-simultaneous immersion			
	in hands		between hands		in hands		between hands	
	mean	SD	mean	SD	mean	SD	mean	SD
1	0.04	0.51	0.07	0.58	0.33	0.46	0.12	0.52
2	0.77	0.20	0.71	0.22	0.81	0.18	-0.40	0.18
3	0.80	0.16	0.79	0.15	0.85	0.09	0.67	0.11
4	0.55	0.30	0.12	0.20	0.48	0.44	0.21	0.38
5	0.27	0.40	0.36	0.40	0.38	0.41	0.41	0.36
6	0.64	0.25	0.61	0.18	0.85	0.13	0.86	0.15
7	0.96	0.05	0.89	0.08	0.95	0.04	0.57	0.14
8	0.61	0.39	0.48	0.40	0.72	0.25	-0.08	0.36
mean	0.58	0.28	0.50	0.27	0.67	0.25	0.30	0.28
SD	0.28	0.14	0.28	0.16	0.22	0.16	0.39	0.14

The PCC decreases when the distance between the compared fingers of one hand is increased: 0.65 for the neighbouring fingers to 0.53 for the thumb and little finger. The differences are on the edge of significancy (p=0.05).

When the neighbouring fingers are tested for all possible combinations, the fingers with the highest correspondence in innervation (index - middle and ring - little finger) do not have higher PCC's than those with different innervation (thumb - index and middle - ring finger) (Table 7.7). The relation between the middle and ring finger is better than all the other combinations.
The PCC of the neighbouring fingers was higher for the non-simultaneous immersion than for the simultaneous immersion ($n=72$, $p < 0.05$).

Table 7.7 Pearson Correlation coefficients of neighbouring fingers (n=8 for every cell).

	simultaneous immersion		non-simultaneous immersion	
	left hand	right hand	left hand	right hand
thumb-index	0.54 ± 0.44	0.54 ± 0.44	0.76 ± 0.24	0.81 ± 0.20
index-middle	0.45 ± 0.55	0.51 ± 0.47	0.70 ± 0.39	0.63 ± 0.51
middle-ring	0.71 ± 0.43	0.87 ± 0.08	0.93 ± 0.05	0.89 ± 0.12
ring-little	0.39 ± 0.53	0.69 ± 0.28	0.62 ± 0.39	0.65 ± 0.39

stability of rectal temperature

The rectal temperature remained relatively constant throughout the experiment. The standard deviation was less than 0.1°C in every experiment and averaged 0.045°C. In the second experiment of subjects 5 and 6 the rectal sensor was damaged, and no data were available for these experiments.

The amount of energy applied by radiation to the subjects to control the rectal temperature varied significantly between subjects from 0 to 3.8 MJ and was not different between simultaneous and non-simultaneous immersion.

The average heat transferred by the two hands to the water was also constant. The heat transferred from the 15th to 25th minute was 54.8 W and from the 35th to 45th minute was 53.5 W. This is not significantly different (paired t-test, $p>0.05$).

hunting parameters

Table 7.8 presents for each subject, the parameters of the hunting reactions, averaged from minute 10 to 40, for the 10 fingers and for the simultaneous and non-simultaneous immersion tests.

Table 7.8 Hunting parameters and average values (10 - 40 min.) for each subject, averaged for the ten fingers and simultaneous and non-simultaneous immersion. The heat transfer is the sum of both hands.

Subject	$\bar{T}_{fi}$ pre-imm. (°C)	T_{min} (°C)	Δt_{onset} (min)	T_{max} (°C)	Period (min)	Amplitude (°C)	$\bar{T}_{fi}$ imm. (°C)	Heat Transfer (W)	T_{re} (°C)	T_w (°C)
1	34.9	11.6	6.4	14.5	11.2	2.9	13.1	73.2	36.9	9.9
2	33.4	10.8	7.4	13.6	11.3	2.7	12.1	36.9	36.8	9.4
3	34.6	18.3	4.5	18.7	5.2	0.4	16.8	80.4	36.5	10.4
4	35.1	12.3	4.5	15.4	8.5	3.1	14.8	78.1	37.0	10.3
5	32.1	10.6	9.2	14.3	10.9	3.8	12.8	49.5	36.4	9.8
6	35.0	10.4	11.6	11.5	8.2	1.1	11.6	36.5	36.8	9.5
7	35.2	16.5	6.4	17.2	11.5	0.7	13.7	53.9	37.2	10.0
8	34.7	10.9	5.7	11.4	8.0	0.5	10.7	38.4	37.3	9.9
Mean	34.4	12.7	7.0	14.6	9.3	1.9	13.2	55.9	36.9	9.9
SD	1.0	2.8	2.3	2.4	2.1	1.3	1.8	17.6	0.3	0.3

7.4 Discussion

synchronization

When the hands are immersed non-simultaneously (NS), the amount of synchronization between the hands is lower than within a hand (Table 7.3). This means that CIVD in NS immersed fingers starts at different moments. When the hands are immersed simultaneously (S) it is more likely that CIVD starts at the same time in the fingers of the two hands. For the analysis within a hand, it does not matter if this hand is immersed simultaneously with another or not; the amount of synchronization is about the same. For the neighbouring fingers, however, a higher correlation was found in NS as compared to S (Table 7.7). The reason for this difference is unknown.

The results confirm the observations of Burton and Edholm (1955) that CIVD starts at different times in the fingers when they are immersed non-simultaneously. However, in some subjects synchronization between the fingers of different hands occurs in NS immersion (see Fig. 7.1). The inter subject variability is large.

Our results are also in general agreement with the observations of Greenfield et al. (1951a), who immersed the left and right index finger of three subjects in water of 0-6°C simultaneously and 5 and 10 minutes apart. When the immersion was performed simultaneously, the responses of the two sides became asynchronous after the heat of the tissue was eliminated. During the immersion period of the non-simultaneous test, the initial behaviour of each finger was independent of what was

happening in the other. The results of only one subject were shown, but it was stated that two other subjects behaved similarly.
In Lewis' work (1930) the curves of the finger temperatures of both hands became concordant after about 45 minutes. In our experiment the immersion time never exceeded 47 minutes. Only one example of non-simultaneous immersion was presented in his publication, which makes it impossible to determine if this can be considered as a normal response.

correspondence
The amount of correspondence, as calculated by the PCC, yielded similar results as the synchronization analysis: the PCC was lowest between the hands for NS immersion (0.30). This is not surprising, since the similarity in shape between two finger skin temperature registrations is closely related to timing aspects (onset of CIVD).
The relatively independent finger temperature fluctuations in NS immersed hands suggests either that central control is minimal and that a peripheral component has to play a role in the initiation of CIVD, or that different vasomotor control centra exist for each hand, for example one in the left and one in the right side of the medulla oblongata.
Another explanation for the similarity in hunting reactions within a hand, and not between hands in NS immersion is reflex vasodilation. Recently, Blumberg and Wallin (1987) showed that intra neural stimulation of a peroneal nerve resulted in reflex vasodilation, which was stronger in the stimulated foot than in the opposite foot. Reflex vasodilation is probably the result of stimulation of thin afferent fibres. In this study the cold stimulus might have stimulated these fibres.

inter subject variability
In this study and the study in the previous chapter enormous differences between subjects existed in heat transfer, local skin temperature and the PCC's. Part of the explanation for the inter subject variability can be found in the fact that every subject has a specific threshold in core temperature above which heat transfer by the hands is started (Chapter 5). This threshold was not determined in the investigation reported in this chapter. Table 7.8 shows that the threshold can not be absolute: subject 3, for instance, has a low T_{re} an the highest heat transfer. The threshold is probably subject-specific, and the esophageal temperature will probably be a better indicator than the rectal temperature, since it closely reflects the blood temperature. It may therefore well be that some subjects had a core temperature above their threshold, leading to central induced heat elimination from the hands. This hypothesis will be tested in chapter 9.

comparison with the previous chapter
Although the PCC of neighbouring fingers is almost identical in both investigations (Fig. 7.2), the mean PCC of all finger combinations in one hand differs: 0.63 in the present investigation as compared to 0.55 in the previous investigation; this was a significant difference ($p<0.05$).

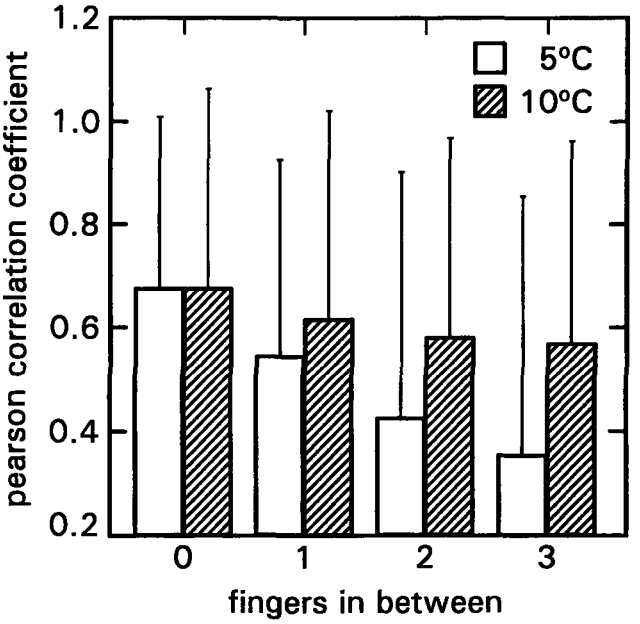

Fig. 7.2 Pearson Correlation Coefficients (PCC) for fingers with 0 (n=128), 1 (n=96), 2 (n=64) and 3 (n=32) fingers in between (hatched bars). The open bars are data from the previous chapter with respectively 48, 36, 24 and 12 data points. The standard deviation is shown by thin solid vertical lines as a rough indicator of the variation, since correlations do not have a normal distribution.

When the compared fingers are separated by other fingers, the PCC was reduced much more in the previous investigation. In the current investigation the PCC between thumb and little finger is 0.21 higher. This means that the fluctuations were more independent in the previous investigation, and that the current investigation involves a more centrally directed way of body heat elimination.
The present investigation differs from the previous one in number of immersed hands (two versus one), water bath temperature (10°C versus 5°C), ambient conditions (temperature 31°C versus 22°C, relative humidity 52% versus 22%) and core temperature (kept constant by an external heat source versus continuous decrease). It is likely that the differences in ambient conditions and core temperature lead to a higher body heat content in the present investigation, which causes a more centrally controlled way of body heat elimination.

The relatively higher influence of central body heat elimination in this investigation can also be seen when the CV of the calorimeter is compared to the CV of the local skin temperatures. In this investigation the CV of the calorimeter was 43% of the CV of the averaged local skin temperatures.

In the previous investigation the CV of the calorimeter was only 31% of the CV of the local skin temperatures. This means that more synchronization has occurred in the present investigation.

In the previous chapter fingers sharing the same somatic nerves were shown to have higher Pearson correlation coefficients than neighbouring fingers with different innervation. This was not found in the present investigation. The middle finger and ring finger showed the best agreement. When the body core is relatively warm, as was the case in this experiment compared to the previous one, the excess body heat will be more easily transferred by the fingers to the water and nervous involvement may be less important. In chapter 13 (general discussion) an in depth coverage of this topic is given.

constant core temperature

The attempt to keep the core temperature within small margins succeeded well. The average SD was only 0.045°C. This resulted in a rather constant heat transfer of the hands to the water.

7.5 Summary

In an attempt to quantify the contribution of central and peripheral mechanisms to blood flow in the hands during immersion in cold water, eight male subjects immersed their hands simultaneously (S) and five minutes after each other (NS) in water of about 10°C. The similarity between the onset times of CIVD was used as a quantitative value for the amount of synchronization between hunting reactions. The Pearson Correlation Coefficient (PCC) was used as an indicator for the amount of correspondence between two hunting reactions.

In NS immersion, the hunting reaction of the two immersed hands was generally not synchronous (only in 14% of the cases synchronization occurred). In S immersion synchronization between two hands occurred more often (in 20% of the cases), but inter subject differences were large. The amount of synchronization in one immersed hand was about 21%.

The amount of correspondence yielded similar results. The PCC between all finger combinations of different hands was only 0.30 in NS.

The relatively independent finger temperature fluctuations in the fingers of NS immersed hands indicates that, under the experimental conditions of this study, central control is minimal, local vasomotor control exists or that local vasomotor reflexes are mainly limited to one hand.

Within a hand, the mean PCC was 0.63, which implied a greater central influence than in the previous chapter, in which the body heat content and water temperature were lower (PCC = 0.55). The higher central influence for one immersed hand was also shown by the variation in heat transfer of the hand to the water, which was 43% of the average fluctuation in finger temperature and only 31% in the previous investigation.

Chapter 8

Correspondence in finger skin temperature between a cold immersed hand and a non-immersed hand

8.1 Introduction

When the fingers of a hand are immersed in cold water, it is known that temperature fluctuations may occur not only in the immersed hand, but also in the contralateral hand (Lewis, 1930). The temperature fluctuations in the immersed hand have been investigated many times and are known as cold induced vasodilation (CIVD). However, the temperature fluctuations of the contralateral hand have not been described in much detail. This is unfortunate because these fluctuations may give information about the mechanisms in the human body during the CIVD phenomenon. Concerning these mechanisms two hypotheses can be formulated. The first hypothesis is linked to nervous afferent mechanisms, the second to blood temperature as the afferent stimulus.

first hypothesis. When the finger skin temperature fluctuations in the non-immersed hand are closely related to the finger skin temperature fluctuations of the immersed hand, this would support a neural origin for the CIVD mechanism. Decreased activity of the sympathetic system would open the blood vessels in the periphery, which would lead to a synchronized increase in blood flow in both hands.

second hypothesis. On the other hand the temperature fluctuations of the non-immersed hand may be out of phase with those of the immersed hand. In this case blood temperature may be a dominating factor of the blood flow in the non-immersed hand. The relatively large heat loss of the immersed hand during the vasodilation phase (often more than 50 W) leads to a cooling of central blood temperature, which may be reflected in the esophageal temperature (e.g., Fig. 5.8). The relatively cold blood returning to the core will stimulate central temperature sensors, which may lead to peripheral vasoconstriction (Zanick and Delaney, 1973). The vasoconstriction will affect both hands, but will probably be hard to see in the cold-water immersed hand, in which CIVD dominates. The non-immersed hand, however, will show a decrease in finger skin temperature. In this way the temperature fluctuations of the fingers of both hands are out of phase. To be more precise, the finger skin temperature profile of the non-immersed hand is expected to be in phase with the body core temperature and the finger skin temperature of the immersed hand is expected to be out of phase with the body core temperature.

It was the purpose of this investigation to establish the relation between the temperature fluctuations in the immersed hand, the non-immersed hand and the blood temperature, quantified by the

esophageal temperature, to discriminate between the two hypotheses formulated above. The Pearson correlation coefficient (PCC) is used to estimate the amount of correspondence between the finger skin temperatures of the immersed and non-immersed hand and the esophageal temperature. Time lags will be taken into account by calculation of the cross correlation coefficient functions. The relation was established for two thermal states of the body: slightly warm and slightly cold. When the body is slightly warm, the sympathetic activity is reduced and heat transfer to the environment is enhanced. This may lead to a better correspondence between the finger skin temperature fluctuations in the two hands.

8.2 Materials and methods

subjects

Seven male subjects participated in the study. Their relevant anthropometric data are presented in Table 8.1. The subjects were fully informed of the purpose of the study and of their right to withdraw from experimentation at any time and gave their consent.

The volume of the right hand was estimated by water displacement. The palmar side of the right hand was photocopied. The contours of the hand were marked and the surface area was determined by a computerised planimeter.

Table 8.1 Anthropometric characteristics of the subjects.

subject	age	weight	stature	body surface area	right hand palmar surface area	right hand volume
	years	kg	cm	m^2	cm^2	cm^3
1	36	75	188	2.00	167	452
2	28	84	189	2.11	166	430
3	22	75	187	2.00	188	445
4	31	55	172	1.65	148	330
5	23	70	178	1.87	160	410
6	21	70	183	1.91	157	416
7	23	60	178	1.75	154	390
mean	26	70	182	1.90	163	410
SD	6	10	6	0.16	13	41

methods

The temperature of the distal phalanx of each finger was measured by copper-constantan thermocouples (par. 3.3.1). The skin perfusion of the non-immersed middle finger was determined by laser Doppler flowmetry (par. 3.2). Three thermocouples were used to calculate the mean body skin temperature ($\bar{T}_{sk}$) (par. 3.3.2). The core temperature was determined rectally and in the esophagus (par. 3.3.3).

The heat transfer of the immersed hand(s) was determined by calorimetry (par. 3.5). The body heat content was calculated according to par. 3.3.4.

procedure

Each subject was investigated once in the morning. During the four hour test the right hand was immersed for 40 minutes in 6°C water twice: once with a relatively cool body and once with a relatively warm body. The odd numbered subjects started with the cool session, the even numbered with a warm session.

In the cool session, the body was cooled during a 80 minute exposure to air at 21°C while lightly dressed in a T-shirt and shorts, and by drinking 250 ml ice water 15 minutes prior to the immersion.

In the warm session, the body was warmed during a 80 minutes exposure to air at 31°C (40%RH) while covering the subject with an extra layer of clothing, and by drinking 250 ml water, as hot as the subject could tolerate, 15 minutes prior to the immersion.

The time schedule is summarized in Fig. 8.1.

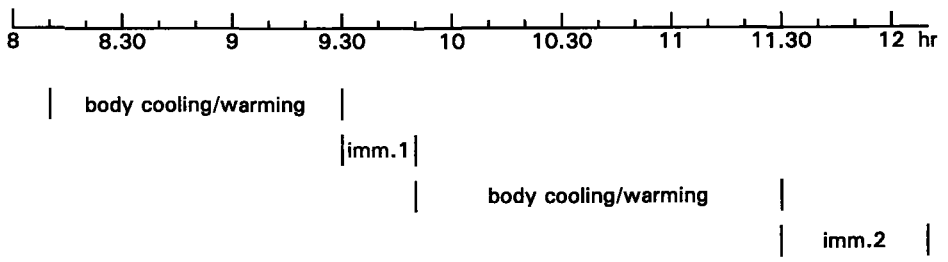

Fig. 8.1 Time schedule of the experiment.

At about 9.30 hours the first immersion took place, at about 11.30 the second immersion started. During the immersion the subject was seated on a chair with his chest against the back-rest. The right hand was hanging down in a calorimeter water bath and the left hand was on the same height on a support, leaving the finger tips in the open air.

At the beginning of the immersion period and two minutes and five minutes later, the subjects were asked to rate their pain and temperature sensation (see par. 3.6). The rating was repeated every five minutes until the end of immersion.

data processing
The signals from the thermocouples, thermistors, and flow meter and thermopile of the calorimeter were sampled every 10 seconds.

8.3 Results

correspondence
In Fig. 8.2 the temperature profiles are shown of the middle finger of the immersed and non-immersed hand for each subject for the cool (dotted lines) and warm (solid lines) condition. Also, the esophageal temperature is shown.

In Fig. 8.2 it can be seen that, in general, there is almost no relation between the three temperature profiles. In the immersed hand the finger skin temperature (T_{fi}) first decreases, followed by the hunting reaction. The finger skin temperatures of the non-immersed hand are fairly constant at about 35°C. When the body is cool, T_{fi} of the non-immersed hand is about 1°C less. The esophageal temperature (T_{es}) generally drops, since the immersed hand transfer considerable amounts of heat to the water.
The correlation between T_{fi} of the left and right hand was less than 0.20 for both the warm and cool condition. The correlation between T_{fi} of the immersed hand and T_{es} was -0.07 for the cool condition and -0.11 for the warm condition. All correlations were not significant. Including a time lag in the calculation of the cross correlation coefficient function, did not improve the correlations.
This means that there was no relation between the temperature fluctuations of the fingers of both hands and no relation between the temperature fluctuations of the fingers and the esophageal temperature. This means that both hypotheses were not supported.

physiological parameters
The core, body skin and finger skin temperatures during the immersion (10th to 40th min) are shown in Table 8.2. Also shown are the water bath temperature, the heat transfer as determined by the calorimeter, the calculated body heat content and the laser Doppler blood flow.

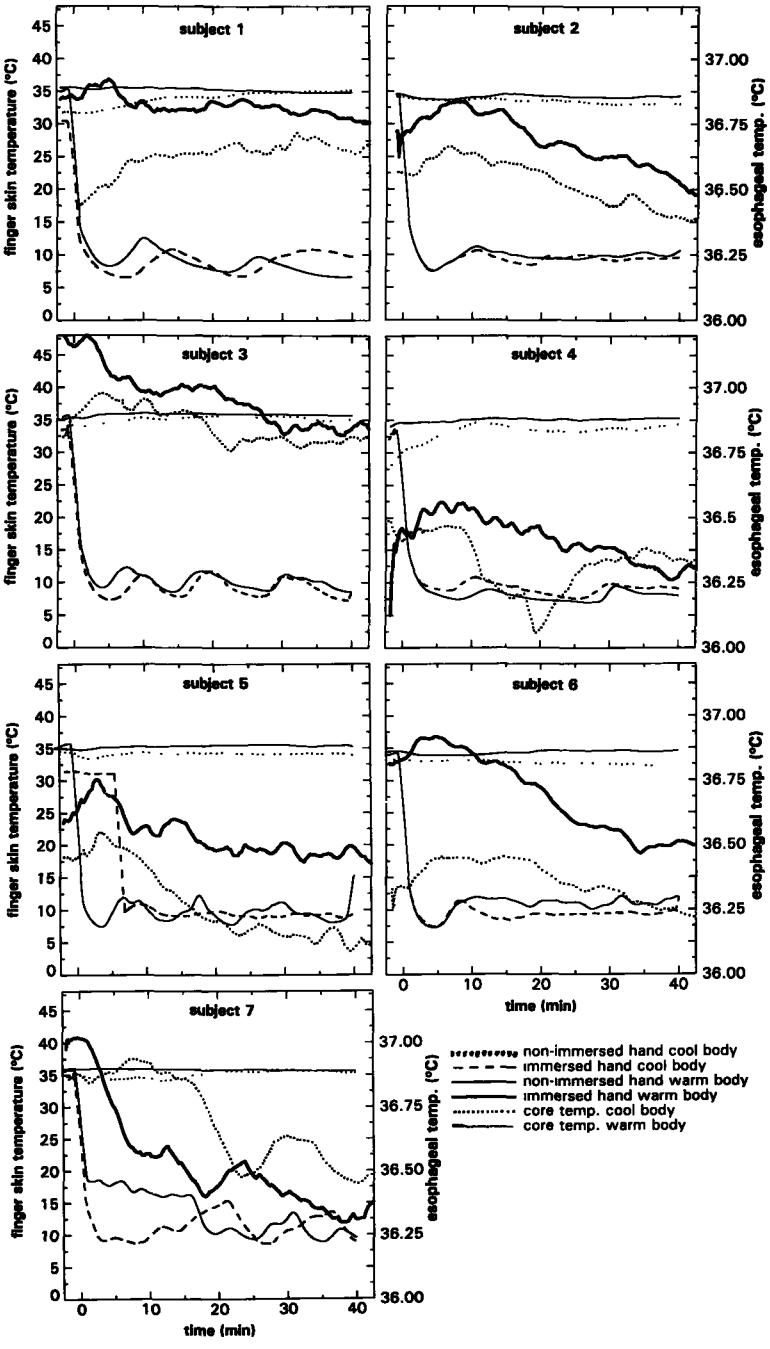

Fig. 8.2 Middle finger skin temperature for the non-immersed (fat), immersed hand and esophageal temperature (almost horizontal lines) in °C before and during immersion. The temperature profiles are shown for each subject for the cool (dotted) and warm (solid lines) body condition.

Table 8.2 Physiological measurements (see list of abbreviations) recorded during the cool and warm sessions for all subjects. The mean values are shown ± the SD within subjects. The SD in the last row denotes the SD between subjects. * = significantly different between cool and warm (paired t-test, $p < 0.05$).

subject	T_{es} (°C)		T_{re} °C		$\bar{T}_{sk}$ (°C)		T_w (°C)	
	cool	warm	cool	warm	cool	warm	cool	warm
1	36.7 ± 0.02	36.8 ± 0.02	36.9 ± 0.04	37.3 ± 0.02	33.6 ± 0.18	34.6 ± 0.20	6.0 ± 0.03	6.1 ± 0.01
2	36.5 ± 0.08	36.6 ± 0.09	36.7 ± 0.04	36.9 ± 0.03	33.9 ± 0.05	33.9 ± 0.17	5.9 ± 0.02	5.8 ± 0.06
3	36.8 ± 0.05	36.9 ± 0.07	37.2 ± 0.07	37.3 ± 0.04	33.6 ± 0.64	34.9 ± 0.12	6.0 ± 0.03	6.0 ± 0.04
4	36.3 ± 0.09	36.4 ± 0.07	36.5 ± 0.06	36.6 ± 0.06	34.2 ± 0.22	34.6 ± 0.09	5.9 ± 0.01	5.9 ± 0.02
5	36.2 ± 0.07	36.5 ± 0.04	36.6 ± 0.08	36.9 ± 0.03	34.1 ± 0.14	34.7 ± 0.03	5.9 ± 0.02	6.0 ± 0.03
6	36.3 ± 0.08	36.6 ± 0.12	36.6 ± 0.05	37.2 ± 0.06	34.2 ± 0.03	34.2 ± 0.16	5.9 ± 0.03	6.0 ± 0.07
7	36.6 ± 0.15	36.4 ± 0.08	37.2 ± 0.06	37.3 ± 0.08	34.2 ± 0.06	34.1 ± 0.07	5.9 ± 0.05	6.0 ± 0.01
mean	36.5	36.6	36.8*	37.1	34.0	34.4	5.9	6.0
SD	0.2	0.2	0.3	0.3	0.3	0.3	0.0	0.1

sub-ject	Heat transfer (W)		Doppler flow (a.u.)		$\bar{T}_{fi}$ left (°C)		$\bar{T}_{fi}$ right (°C)	
	cool	warm	cool	warm	cool	warm	cool	warm
1	33.5 ± 15.0	35.1 ± 7.8	3.2 ± 0.28	2.5 ± 0.33	33.8 ± 0.39	34.5 ± 0.16	9.0 ± 1.02	8.2 ± 0.87
2	39.2 ± 10.8	45.4 ± 5.1	0.7 ± 0.11	1.6 ± 0.28	33.1 ± 0.24	34.0 ± 0.14	8.8 ± 0.43	9.2 ± 0.24
3	49.1 ± 27.7	60.2 ± 6.7	2.3 ± 0.45	2.8 ± 0.21	34.7 ± 0.21	35.4 ± 0.07	9.4 ± 1.50	9.5 ± 0.42
4	38.9 ± 13.4	36.3 ± 6.5	2.0 ± 0.64	2.7 ± 0.29	33.8 ± 0.32	34.7 ± 0.10	8.7 ± 0.83	7.8 ± 0.41
5	41.3 ± 8.6	56.4 ± 6.0	3.3 ± 0.24	3.0 ± 0.13	34.4 ± 0.08	35.5 ± 0.11	8.9 ± 0.30	9.5 ± 0.90
6	50.8 ± 12.0	67.0 ± 10.2	1.4 ± 0.29	2.2 ± 0.31	32.4 ± 0.16	33.9 ± 0.24	9.6 ± 0.59	11.9 ± 0.73
7	55.2 ± 14.2	60.0 ± 15.6	3.5 ± 0.40	3.9 ± 0.31	34.6 ± 0.32	35.3 ± 0.10	11.1 ± 1.62	11.4 ± 1.60
mean	44.0	51.5	2.3	2.7	33.8*	34.7	9.3	9.7
SD	7.2	11.7	1.0	0.7	0.8	0.6	0.8	1.4

subject	Body heat content (kJ)	
	cool	warm
1	9431 ± 3.0	9541 ± 6.3
2	10545 ± 3.5	10578 ± 2.4
3	9480 ± 6.7	9565 ± 3.8
4	6883 ± 4.8	6912 ± 2.2
5	8756 ± 2.3	8839 ± 5.8
6	8777 ± 3.6	8854 ± 7.8
7	7594 ± 9.6	7585 ± 8.9
mean	8781*	8839
SD	1227	1247

As can be seen from Table 8.2 the differences between the warm and the cool condition were small. Only rectal temperature (T_{re}), body heat content and the temperature of the left hand were significantly different. In the warm body condition, subject 7 initially had a slightly higher T_{es} when the right hand was immersed (Fig. 8.2). During the initial 15 minutes of hand immersion, however, the vasodilation in the right hand was so strong (Fig. 8.2), that the esophageal temperature dropped sharply during the experiment and even became lower than in the cool condition.

hunting parameters

In Table 8.3 the results concerning the hunting reaction are shown.

Table 8.3 Parameters of the hunting reaction, averaged over all subjects. * is statistically significant between cool and warm condition (ttest; Kruskal-Wallis-test for correlations).

hand	right				left			
core	cool		warm		cool		warm	
	mean	SD	mean	SD	mean	SD	mean	SD
$\bar{T}_{fi}$ pre-imm. (°C)	32.0*	1.3	33.0	1.2	34.0	1.0	34.1	1.5
T_{min} (°C)	7.6*	0.9	9.4	3.3	33.2*	0.9	34.0	1.1
Δt_{onset} (min)	6.4*	2.0	5.1	1.6	3.6	1.1	4.0	3.5
T_{max} (°C)	10.0*	1.0	12.2	2.6	34.0*	0.8	34.5	1.0
Amplitude (°C)	2.4	1.3	2.8	1.7	0.8*	0.8	0.5	0.5
Period (min)	10.2	5.4	8.8	5.1	6.0	3.9	5.5	3.7
$\bar{T}_{fi}$ (°C)	9.3	0.9	9.7	1.5	33.8*	0.9	34.7	0.7
Mean correlation of all fingers in immersed hand	0.85*	0.14	0.70	0.32	0.64*	0.30	0.37	0.44

Before immersion, the left hand was warmer than the right hand. The right hand was cooler when the body was cooled.

In the cool body condition, T_{min} of the immersed hand was lower and occurred later than for the warm body condition. Also, T_{max} was lower. In the non-immersed hand, the minimal and maximal finger skin temperatures were lower in the cool body condition than in the warm body.

The finger skin temperature fluctuations had more similarity within a hand when the body was cold than when the body was warm, both for the immersed and the non-immersed hand.

8.4 Discussion

first hypothesis

During the immersion of the right hand in 6°C water, no relation was found between the temperature fluctuations in the immersed hand and the non-immersed hand. This means that no synchronous effect of sympathetic activity on both hands could be found. This finding is not in agreement with the results of Lewis (1930), but agrees with the overall results of later research, as discussed by Dana et al. (1969). However, Dana et al. (1969) concluded that hunting occurred at different times in different fingers, even when they were all exposed simultaneously. In the present study and in the studies in previous chapters, it was clearly shown that the hunting reaction in the fingers of the same immersed hand had similarities, especially in the neighbouring fingers.

second hypothesis

The heat transfer of 33.5 to 67 W of the right hand to the water (Table 8.2), caused a decrease in core temperature during the immersion. However, the fluctuations in finger skin temperatures were not related to the fluctuations in core temperature. Thus, a temporary increase in finger skin temperature due to cold induced vasodilation, and, hence, a temporary increase in heat loss, was not followed by a greater steepness of the decrease in core temperature. Probably, the finger skin temperature changes are largely buffered by counter current heat exchange (see par. 2.2.1) causing a slow decrease of the core temperature.

initial vasoconstriction

It was expected that the Doppler blood flow of the left finger would be higher when the body was warmer. This was not the case for subjects 1 and 5, despite the fact that the finger skin temperatures were higher in the warm body condition. As discussed in par. 3.2, Doppler blood flow only partially measures the blood flow through the arteriovenous anastomoses deep in the skin. Moreover, laser Doppler flowmetry reflects quick changes in blood flow, for instance due to coughing. In most subjects a short vasoconstriction was seen in the left middle finger immediately after immersion of the right hand. This probably reflected a general sympathetic increase due to pain (Folkow et al., 1963). The vasoconstriction is slightly visible in the slower reacting middle finger skin temperature of subjects 1, 2, 3, 5 and 7 in the cool body condition (Fig. 8.2).

conclusion

It can be concluded that the finger temperature fluctuations of the immersed and non-immersed hand are independent and that no common control seems to be present. The central blood temperature, as assessed by esophageal temperature, does not reflect the relatively fast temperature fluctuations in the fingers. The possibility that the left hand and right hand have different vasomotor control centres is supported.

Although the differences in body heat content were minimal between the two investigated thermal states of the body, differences in hunting parameters were found: T_{min} and T_{max} were lower for the cool body and onset time was longer. The hunting reaction, therefore, is sensible to body temperature.

8.5 Summary

To identify the amount of common vascular control between the two hands, seven subjects immersed one hand in 6°C water, and exposed the other hand to 31°C air. The finger skin temperatures of the immersed hand showed a hunting reaction, while the finger skin temperatures of the non-immersed hand showed small fluctuations around 35°C. The fluctuations of the finger skin temperatures of the immersed and non-immersed hand were not related. Thus, common control is absent and it is likely that separate vasomotor control centra for the right and left hand exist.
The immersed hand lost on average 44 W when the body was slightly chilled before the hand immersion and 52 W when the core was slightly warmed previously. This heat loss caused a slow decrease in core temperature during immersion. However, the body core temperature did not reflect the changes in finger skin temperature during immersion of the hand, probably due to counter current heat exchange. The small difference in body thermal status caused significant changes in the hunting parameters. In the warm body onset of cold induced vasodilation occurred sooner and minimum and maximum finger skin temperatures were higher. This illustrates the high sensitivity of the hunting reaction for body thermal status.

Chapter 9*

Interindividual differences in the hunting reaction and the effect of body core and water bath temperature

9.1 Introduction

In the previous chapters it was found that the hunting reactions of the fingers in one hand were more similar when the body core temperature and water temperature were higher. However, both core and water temperature were raised simultaneously in chapter 7 as compared to chapter 6, and were not investigated separately. Chapter 8 showed that even small differences in body thermal status caused significant differences in the hunting parameters.
The present chapter presents an experiment in which the core temperature and water temperature were varied independently. The core temperature during hand immersion was related to the individual thresholds in core temperature for finger vasodilation (see chapter 5). This is to verify if this threshold might explain the large interindividual differences found in the hunting-characteristics.

9.2 Materials and methods

subjects
Eight male subjects participated in the study. Their relevant anthropometric data are presented in Table 9.1.

*Parts of this chapter have been published in: Daanen, H.A.M., Heus, R. (1995). Cold Induced Vasodilation. Chapter 7 in: Tikuisis, P. (ed.): Handbook on predicting responses to cold exposure. Report A-C/243 (Panel 8) TR/20.

Table 9.1 Anthropometric characteristics of the subjects.

subject	age	weight	stature	body surface area
	years	kg	cm	m^2
1	21	69	185	1.91
2	21	74	178	1.91
3	23	60	172	1.71
4	21	65	173	1.77
5	26	89	184	2.12
6	19	69	181	1.88
7	19	75	184	1.97
8	34	74	188	1.99
mean	23.0	71.9	181	1.91
SD	5.0	8.6	0.06	0.13

methods

The temperature of the distal phalanx of each finger of both hands was measured by copper-constantan thermocouples. During the experiments the rectal and esophageal temperature of the subjects were measured (par. 3.3). Three thermocouples were used to calculate the mean body skin temperature ($\bar{T}_{sk}$) (see par. 3.3.2). The heat transfer of the immersed hand(s) was determined by calorimetry (par. 3.5). A heat flux transducer was placed on the volar surface of the left index finger in the first part of every session to determine the threshold for finger vasodilation. The body heat content is calculated according to par. 3.3.4. Pearson correlation coefficients were calculated according to par. 3.11.

procedure

The time schedule is summarized in Fig. 9.1.

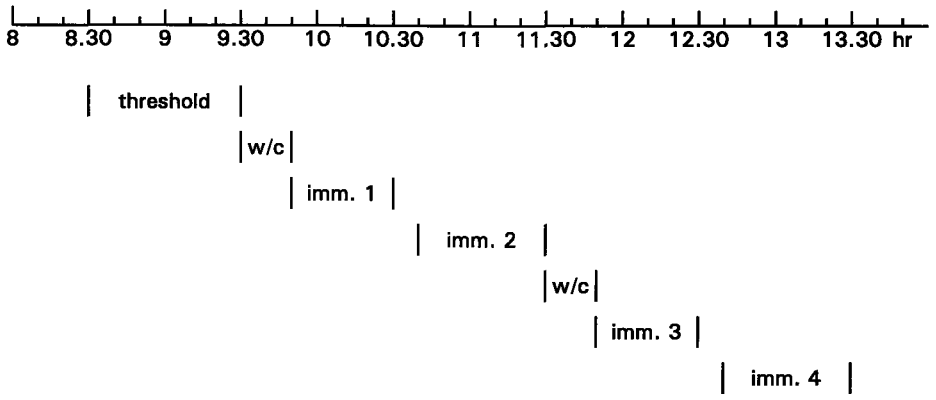

Fig. 9.1 Time schedule of the experiment. w/c is warming or cooling of the body core according to Table 9.2; imm. is immersion of the hands in cold water.

After explanation of the purpose of the investigation, the subject was instrumented with temperature sensors (see above). Each subject was lightly dressed in T-shirt and shorts. Hereafter, the subject entered a climatic chamber set at 20°C and at 50% relative humidity, where the esophageal threshold for finger vasodilation was determined (chapter 5). The left hand of the subjects was immersed in a water bath of 15°C. As soon as the heat transfer from the index finger had decreased to almost zero, the subjects started cycling on an ergometer (Lode Angio) with an external power of 80 W. About two minutes after the occurrence of a sharp increase of the heat flux from the index finger, the exercise was stopped. The exercise was restarted when the HF from the index finger had decreased to zero. The maximal immersion time never exceeded forty minutes.

After the determination of the threshold, the subjects entered another climatic chamber, which was warmer (25°C, 50% relative humidity). In this room the subject performed four 40-minute cold water immersions of both hands. The second hand was immersed three minutes after the first. The first hand to be immersed was changed each immersion, e.g., left - right - left - right or right - left - right - left.
The immersions were performed at two different core temperatures (relatively warm and relatively cool) and two water bath temperatures (cold (about 8.5°C) and very cold (about 5°C)) (Table 9.2). Due to incomplete heat removal by the heat exchanger of the calorimeter, the temperature of the water increased during the immersion by 1.0 to 1.9°C. The experimental conditions were balanced in order to be able to eliminate order effects.

Table 9.2 Immersion protocol (balanced).

subject	Immersion 1		Immersion 2		Immersion 3		Immersion 4	
	core	water	core	water	core	water	core	water
1	warm	cold	warm	very cold	cool	very cold	cool	cold
2	cool	cold	cool	very cold	warm	very cold	warm	cold
3	warm	very cold	warm	cold	cool	cold	cool	very cold
4	cool	very cold	cool	cold	warm	very cold	warm	cold
5	warm	cold	warm	very cold	cool	cold	cool	very cold
6	cool	cold	cool	very cold	warm	cold	warm	very cold
7	warm	very cold	warm	cold	cool	very cold	cool	cold
8	cool	very cold	cool	cold	warm	cold	warm	very cold

In order to induce a relatively warm body core, the subject performed 80 W cycling exercise. The exercise period lasted about 6 minutes and about 6 minutes elapsed after the exercise before the immersion period started. Moreover, subjects 5 to 8 were dressed in a bathrobe and long trousers. The relatively cool body core was induced by quiet sitting in shorts and a T-shirt.

During the immersion, the subjects were sitting on a chair in front of the calorimeter with the hands hanging down vertically. The chest was supported by the reversed back rest of the chair. This appeared to be a comfortable body position. During the immersion period the esophageal temperature was controlled by heat radiation on the back of the body. As soon as a decrease in esophageal temperature was seen, the amount of radiation was increased. Strong radiators were placed about two metres from the subjects back as in Chapter 7. The back of the subject was covered with a white towel when radiation was applied. The amount of applied radiation was not recorded.
After each immersion period the subject was warmed again or was sitting quietly, dependent on the protocol in Table 9.2. In the mean time the calorimeter was cooled or rewarmed by the thermostat bath to the required temperature.

data processing
The signals from the thermocouples, thermistors, flow meter and thermopile of the calorimeter were sampled every 16 seconds. The skin temperature, heat transfer and water temperature were each averaged over the immersion period after the 10th minute. Differences between the experimental conditions (cool and warm core, cold and warm water) were tested with ANOVA (module MGLH from SYSTAT). The difference between actual esophageal temperature (T_{es}) and determined threshold in T_{es} was calculated and related to the hunting parameters.

9.3 Results

thresholds

The thresholds for each subject are shown in Table 9.4. In the forty minutes taken for the threshold determination, three threshold measurements could be done for subjects 1, 2, 3 and 6, two for subjects 4, 5 and 7 and only one for subject 8. The stability of the threshold is rather different between subjects. The mean SD (0.10°C) is higher than in chapter 5 (0.07°C). The thresholds were relatively similar with the exception of subject 1 who had a high threshold and subject 7 who had a low threshold.

Table 9.4 Mean and SD of individual thresholds in esophageal temperature (°C) for finger skin vasodilation during a forty minute period. The number of thresholds determined in the forty minute period is shown in the right column.

subject	mean threshold (°C)	SD within subjects (°C)	number of thresholds
1	36.95	0.11	3
2	36.52	0.15	3
3	36.46	0.12	3
4	36.52	0.17	2
5	36.54	0.01	2
6	36.53	0.05	3
7	36.20	0.10	2
8	36.70	0.00	1
mean	36.56	0.10	2.4
SD between subjects	0.23	-	-

effect of body core and water temperature on hunting

In Fig. 9.2, as an example, the hunting reaction of subject 8 is shown for the left and right middle finger. Also, changes in core temperature, water temperature, heat transfer and mean (body) skin temperature are shown. Note that the finger skin temperatures and the heat transfer were higher when the body core was relatively warm.

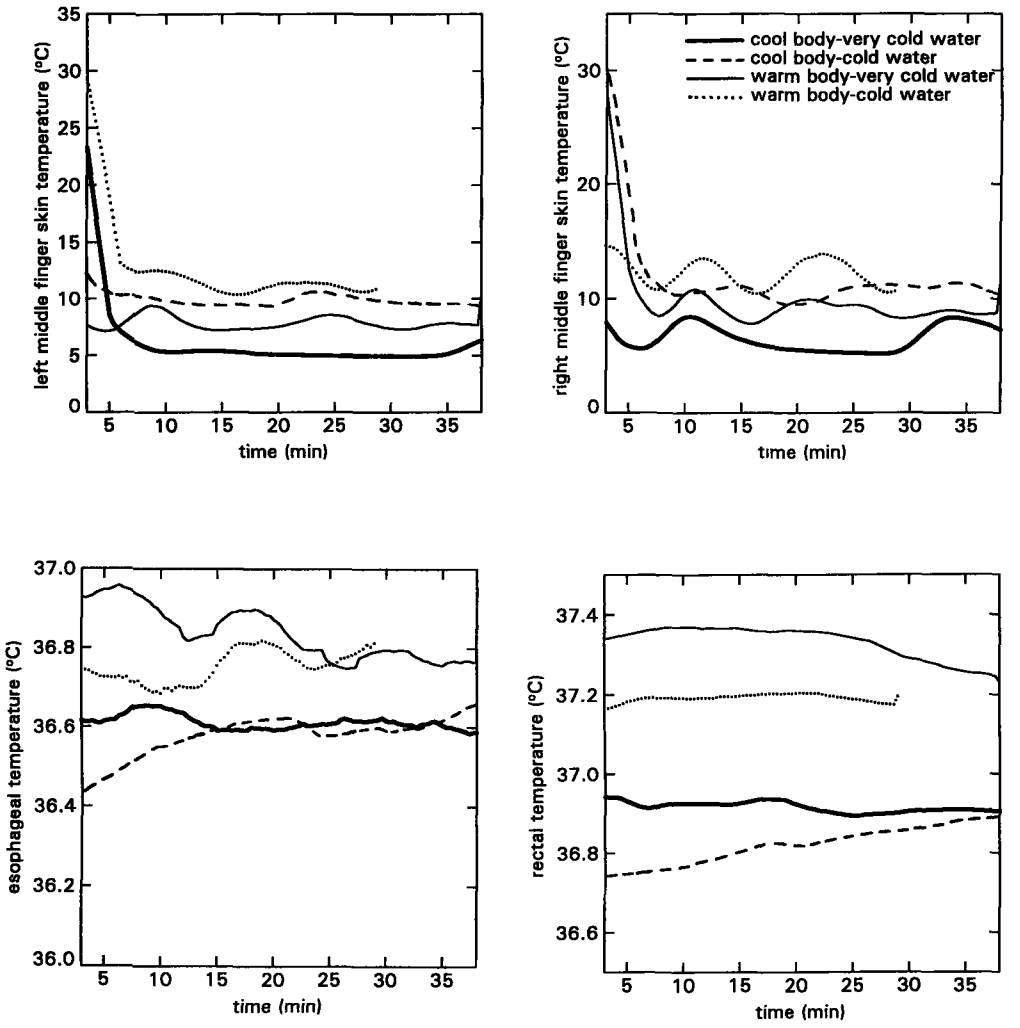

Fig. 9.2a Left and right middle finger skin temperature (°C), esophageal and rectal temperature (°C) for subject 8, shown as an example. Every curve represents one experimental condition. Due to technical problems, the warm body - cold water session was ended 30 minutes after the immersion of the first hand. The results are shown from the start of immersion of the second hand.

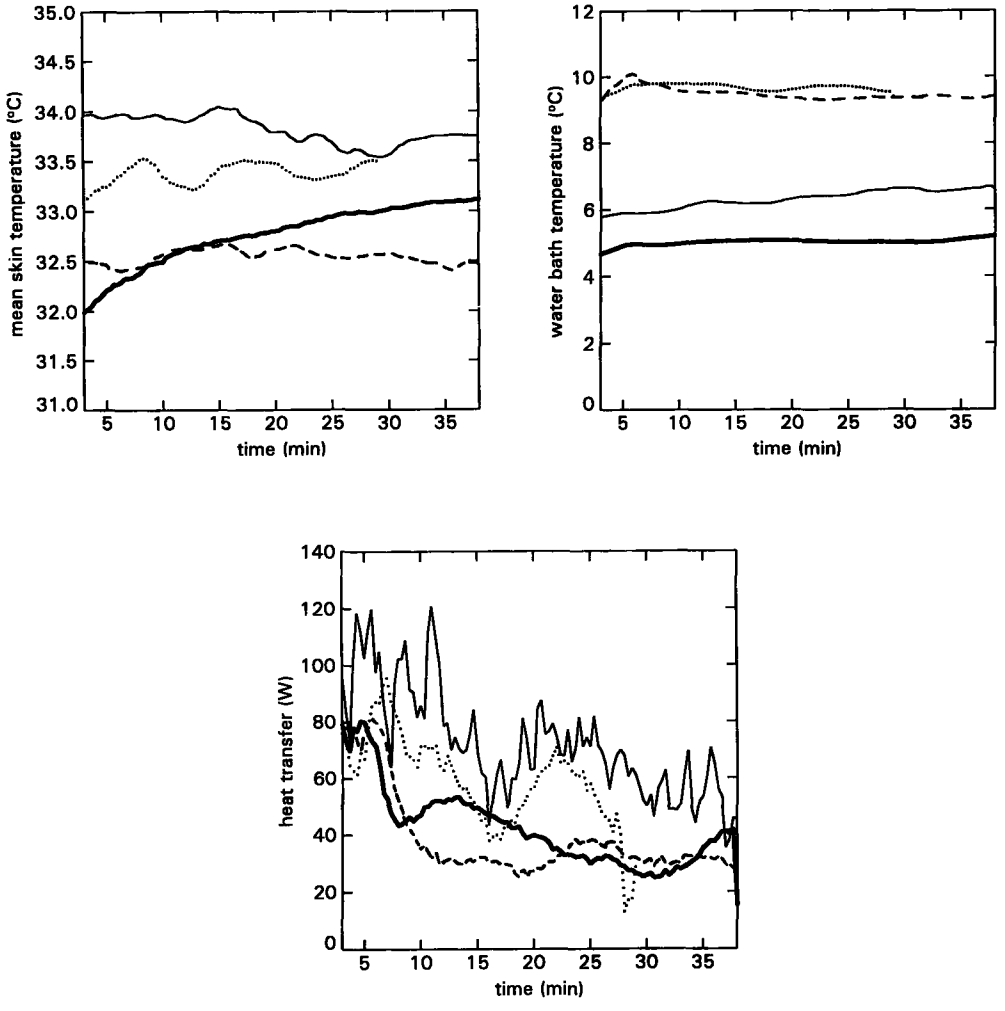

Fig. 9.2b Mean (body) skin temperature (°C), water bath temperature (°C) and heat transfer (W) for subject 8, shown as an example. Every curve represents one experimental condition. Due to technical problems, the warm body - cold water session was ended 30 minutes after the immersion of the first hand. The results are shown from the start of immersion of the second hand.

The averaged results for all experimental conditions are shown in Table 9.5 for each subject. Since some subjects removed their hands shortly before the end of the immersion period, the averages were calculated over a period of 10 to 38 minutes.

Table 9.5 Mean values of the dependent variables from the 10th to 38th minute of immersion for the four experimental conditions. SD within subjects is shown in columns, SD between subjects is shown in the bottom row. The Pearson correlation coefficient (PCC) is the mean value of all immersed fingers and reflects the amount of correspondence between the hunting reactions for all fingers. * is significantly different between cool and warm core; $ is significantly different between cold and very cold water (ANOVA). Correlations are analysed non-parametrically (Kruskal-Wallis test).

variable	**esophageal temp.** (°C)							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	37.0	0.02	37.0	0.01	36.9	0.03	37.0	0.03
2	36.8	0.03	36.9	0.05	37.0	0.03	37.1	0.08
3	36.9	0.07	37.0	0.05	36.7	0.09	36.8	0.07
4	36.8	0.03	36.7	0.02	36.7	0.02	36.7	0.02
5	36.7	0.05	36.7	0.06	36.8	0.07	36.6	0.18
6	36.5	0.05	36.6	0.02	37.0	0.10	36.9	0.06
7	36.9	0.05	36.8	0.03	36.9	0.04	36.7	0.08
8	36.6	0.01	36.6	0.02	36.8	0.05	36.8	0.04
mean	36.8	0.04	36.8	0.03	36.9	0.05	36.8	0.07
SD	0.2	0.02	0.1	0.02	0.1	0.03	0.1	0.05

variable	**rectal temp.** (°C)*							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	37.3	0.02	37.1	0.01	37.3	0.01	37.3	0.00
2	36.5	0.07	36.8	0.05	37.2	0.02	37.3	0.03
3	37.2	0.02	37.2	0.01	37.1	0.07	37.0	0.02
4	37.1	0.01	36.9	0.03	37.0	0.02	37.0	0.02
5	37.0	0.02	37.0	0.03	37.2	0.04	37.3	0.06
6	36.7	0.03	36.8	0.01	37.2	0.03	36.9	0.06
7	37.1	0.02	37.0	0.01	37.2	0.02	37.2	0.05
8	36.9	0.01	36.8	0.03	37.3	0.04	37.2	0.01
mean	37.0	0.02	37.0	0.02	37.2	0.03	37.1	0.03
SD	0.3	0.02	0.1	0.01	0.1	0.02	0.1	0.02

Table 9.5 continued

variable	**mean body skin temp. (°C)**[4]							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	33.9	0.07	33.4	0.08	34.1	0.05	34.0	0.03
2	32.7	0.20	32.7	0.03	33.5	0.19	33.8	0.05
3	32.6	0.07	33.0	0.05	33.1	0.34	34.4	0.12
4	32.5	0.07	33.0	0.08	32.7	0.10	33.1	0.08
5	33.5	0.05	33.4	0.04	35.2	0.14	34.6	0.12
6	34.2	0.35	33.9	0.07	35.9	0.15	35.6	0.18
7	34.4	0.04	34.0	0.03	34.6	0.20	35.0	0.06
8	32.9	0.17	32.6	0.07	33.8	0.14	33.4	0.09
mean	33.4	0.13	33.3	0.06	34.1	0.16	34.2	0.09
SD	0.7	0.10	0.5	0.02	1.0	0.08	0.8	0.04

variable	**body heat content (kJ)**[4]							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	8767	4	8721	4	8770	5	8762	3
2	9238	14	9281	10	9365	9	9403	10
3	7548	8	7573	5	7553	6	7599	11
4	8159	4	8147	5	8148	3	8157	3
5	11208	8	11208	9	11346	5	11294	25
6	8672	14	8675	3	8856	16	8795	19
7	9518	9	9478	3	9539	9	9534	11
8	9267	7	9243	4	9377	15	9338	9
mean	9047	9	9041	5	9119	8	9110	11
SD	1014	4	1011	2	1052	5	1031	7

variable	**water temp. before immersion (°C)**[5]							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	5.7	0.1	8.2	0.1	5.1	0.2	8.3	0.1
2	5.5	0.2	8.3	0.1	6.0	0.1	8.5	0.2
3	4.9	0.3	8.6	0.1	4.3	0.2	8.2	0.2
4								
5	5.7	0.2	8.4	0.2	5.8	0.2	9.0	0.2
6	4.7	0.2	8.6	0.2	7.0	0.2	9.2	0.1
7	5.0	0.3	8.7	0.1	4.8	0.2	8.3	0.2
8	4.4	0.2	8.8	0.1	5.6	0.2	9.2	0.2
mean	5.1	0.2	8.5	0.1	5.5	0.2	8.7	0.2
SD	0.5	0.1	0.2	0.1	0.8	0.0	0.4	0.0

Table 9.5 continued

variable	watertemp. during immersion (°C)[5]							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	6.0	0.0	8.6	0.0	6.0	0.1	8.4	0.1
2	6.1	0.1	8.3	0.1	7.0	0.1	9.7	0.4
3	5.5	0.1	8.9	0.1	5.4	0.2	9.1	0.2
4					8.9	0.6	11.2	0.4
5	7.1	0.2	9.2	0.1	7.6	0.5	11.7	1.8
6	5.9	0.2	10.9	0.4	9.8	0.6	11.3	0.6
7	6.1	0.1	9.2	0.1	5.6	0.1	9.2	0.2
8	5.1	0.0	9.4	0.1	6.4	0.2	9.7	0.1
mean	6.0	0.1	9.2	0.1	7.1	0.3	10.0	0.4
SD	0.6	0.1	0.8	0.1	1.5	0.2	1.1	0.5

variable	pain sensation[*5]							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	1.6	0.5	1.0	0.0	1.0	0.0	1.0	0.0
2	7.2	0.4	3.4	1.1	2.9	0.2	1.5	0.5
3	3.0	0.6	1.8	0.5	2.3	0.8	2.7	0.5
4	4.4	1.2	3.4	1.2	2.2	0.6	1.6	0.2
5	2.6	0.9	1.6	0.9	2.3	0.5	0.8	1.3
6	7.7	1.3	4.6	2.2	2.9	1.1	2.6	0.4
7	3.0	0.7	2.0	0.0	3.1	0.5	1.0	0.0
8	3.3	1.3	0.7	0.4	2.2	0.4	1.3	0.6
mean	4.1	0.9	2.3	0.8	2.4	0.5	1.6	0.4
SD	2.1	0.3	1.3	0.7	0.6	0.3	0.7	0.4

variable	temperature sensation[*5]							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	-4.8	0.4	-4.3	0.4	-4.2	0.4	-4.6	0.5
2	-8.2	0.3	-4.6	0.9	-6.0	0.0	-3.1	0.5
3	-4.5	0.5	-3.3	0.5	-4.0	0.7	-3.0	0.5
4	-6.3	0.6	-6.3	0.6	-3.9	0.4	-3.1	0.9
5	-7.2	1.1	-5.2	1.1	-6.0	0.0	-2.8	1.3
6	-8.2	1.0	-8.0	1.0	-3.9	2.4	-3.3	0.7
7	-3.7	1.0	-2.0	0.0	-2.4	0.5	-2.0	0.0
8	-6.0	0.7	-3.4	0.5	-6.6	0.5	-3.3	0.6
mean	-6.1	0.7	-4.6	0.6	-4.6	0.6	-3.2	0.6
SD	1.6	0.3	1.8	0.3	1.3	0.7	0.7	0.3

Table 9.5 continued

variable	**minimum finger skin temperature (T_{min}) (°C)***							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	6.5	0.2	9.3	0.7	7.8	0.4	9.7	0.8
2	6.6	0.3	8.9	0.6	8.3	0.9	11.2	0.5
3	7.2	1.0	10.6	1.0	8.4	2.6	12.8	1.7
4	6.1	0.6	10.6	1.4	8.0	0.6	10.2	0.4
5	8.6	1.5	10.4	0.6	8.5	0.9	9.9	1.0
6	5.9	0.4	9.9	0.4	10.9	0.7	11.8	0.5
7	8.8	0.7	10.5	0.5	7.1	0.5	13.4	2.3
8	5.5	0.4	10.1	0.4	8.0	1.2	10.7	0.6
mean	6.9	0.7	10.0	0.7	8.4	1.0	11.2	1.0
SD	1.1	0.4	0.6	0.3	1.1	0.7	1.3	0.7

variable	**maximum finger skin temperature (T_{max}) (°C)***							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	10.8	0.6	9.7	0.9	12.1	2.2	13.7	3.5
2	8.9	0.9	11.9	1.6	11.1	1.5	14.2	0.7
3	10.7	1.2	14.8	2.5	13.1	2.8	16.2	2.0
4	10.9	1.9	13.4	0.9	11.3	1.0	13.7	1.4
5	13.7	2.6	15.0	2.9	14.2	2.6	16.5	3.6
6	9.5	1.0	11.3	0.7	17.5	2.0	13.5	1.0
7	11.6	1.5	11.6	0.8	11.3	1.3	17.9	2.5
8	7.4	1.2	11.2	0.4	11.5	1.9	14.1	1.4
mean	10.4	1.4	12.3	1.3	12.8	1.9	15.0	2.0
SD	1.8	0.6	1.7	0.9	2.1	0.6	1.5	1.0

variable	**onset time** (time from immersion to first CIVD) (min)*							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	5.8	0.6	7.4	3.6	10.4	2.9	11.5	4.4
2	5.7	0.8	5.8	1.0	6.2	2.5	8.4	2.1
3	7.5	4.1	10.5	4.0	10.4	7.9	8.0	2.5
4	6.5	3.1	6.4	0.9	12.4	2.3	11.1	2.9
5	7.7	4.4	9.7	2.6	6.7	2.1	10.6	2.5
6	6.7	0.8	14.9	3.8	8.8	2.1	15.2	4.5
7	7.6	5.6	9.3	3.4	7.0	3.8	9.2	5.6
8	6.0	0.6	8.7	5.8	9.2	4.1	9.8	2.6
mean	6.7	2.5	9.1	3.1	8.9	3.5	10.5	3.4
SD	0.8	1.9	2.7	1.5	2.0	1.8	2.1	1.2

Table 9.5 continued

variable	**amplitude** (maximum finger skin temperature - minimum) (°C)*							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	4.3	0.6	0.5	0.6	4.4	2.0	4.0	3.3
2	2.4	1.0	0.9	0.8	2.8	1.4	3.0	0.7
3	3.5	0.9	4.1	1.8	4.7	1.8	3.4	2.0
4	4.8	1.8	2.8	1.1	3.3	1.0	3.5	1.2
5	5.1	1.9	4.5	2.9	5.7	2.7	6.6	3.3
6	3.6	1.1	1.4	0.7	6.6	1.5	1.7	1.3
7	2.8	1.4	1.1	0.7	4.2	1.2	4.5	2.3
8	1.9	1.1	1.1	0.3	3.5	1.8	3.4	1.0
mean	3.5	1.2	2.0	1.1	4.4	1.7	3.8	1.9
SD	1.1	0.4	1.5	0.8	1.2	0.5	1.3	0.9

variable	**period** (time from first to second minimum in CIVD) (min)							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	10.6	1.9	15.4	2.9	11.6	3.8	12.9	2.3
2	16.5	6.1	26.4	3.5	13.2	7.6	11.6	0.9
3	13.4	3.1	11.6	4.6	13.5	4.5	11.4	4.5
4	13.3	3.0	7.0	2.0	11.3	2.0	10.5	0.8
5	11.8	2.0	13.5	4.7	13.9	4.9	10.1	3.8
6	15.1	4.9	13.9	1.7	10.1	0.4	14.3	4.7
7	9.3	2.0	9.5	3.0	11.0	1.3	10.7	3.1
8	21.2	4.8	13.1	5.2	9.9	2.7	11.3	2.0
mean	13.9	3.5	13.8	3.5	11.8	3.4	11.6	2.8
SD	3.5	1.5	5.4	1.2	1.4	2.1	1.3	1.4

variable	**finger skin temp. before immersion** (°C)*							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	23.4	1.0	29.3	3.4	33.3	1.0	33.8	0.4
2	28.2	0.7	31.7	1.0	33.2	0.4	32.4	1.0
3	31.0	0.3	31.4	0.5	33.0	0.7	33.5	0.7
4	26.7	1.0	30.9	1.4	33.7	0.3	31.3	0.9
5	34.5	0.2	33.0	0.3	34.5	0.2	31.9	0.4
6	25.1	1.2	27.0	1.8	35.6	0.2	34.9	0.3
7	33.9	0.2	30.2	1.1	31.5	0.6	33.5	0.7
8	30.9	0.5	31.1	1.1	33.6	0.5	28.6	1.8
mean	29.2	0.6	30.6	1.3	33.5	0.5	32.5	0.8
SD	3.8	0.4	1.7	0.9	1.1	0.3	1.8	0.4

Table 9.5 continued

variable	**finger skin temp. during immersion (°C)***							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	7.9	0.6	9.4	0.2	9.2	0.9	10.7	1.1
2	7.5	0.5	9.6	0.8	9.1	0.6	12.2	1.5
3	9.6	1.0	11.9	1.2	10.8	1.1	14.0	1.7
4	7.9	0.6	11.2	1.0	9.3	0.9	10.9	1.1
5	10.0	1.3	12.9	1.4	11.9	0.8	16.2	3.5
6	7.9	0.7	10.5	0.4	13.5	1.6	12.4	0.5
7	9.7	0.5	10.9	0.2	8.9	0.5	13.8	2.0
8	5.8	0.6	10.5	0.2	9.1	0.8	12.4	1.2
mean	8.3	0.7	10.9	0.7	10.2	0.9	12.8	1.6
SD	1.3	0.3	1.1	0.5	1.6	0.3	1.7	0.9

variable	**Pearson correlation coefficient (PCC)***							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	0.25	0.36	0.11	0.46	0.43	0.32	0.58	0.27
2	0.36	0.48	0.91	0.06	0.32	0.37	0.91	0.08
3	0.57	0.26	0.66	0.23	0.19	0.51	0.67	0.20
4	0.16	0.42	0.90	0.10	0.57	0.28	0.86	0.13
5	0.54	0.27	0.40	0.40	0.02	0.43	0.92	0.06
6	0.36	0.42	0.25	0.50	0.50	0.38	0.52	0.36
7	0.37	0.38	0.11	0.61	0.27	0.48	0.64	0.22
8	0.63	0.23	0.12	0.51	0.59	0.35	0.89	0.09
mean	0.41	0.35	0.43	0.36	0.36	0.39	0.75	0.18
SD	0.15	0.09	0.32	0.19	0.19	0.07	0.15	0.10

variable	**mean heat transfer (W)***							
core	cool				warm			
water	very cold		cold		very cold		cold	
subject	mean	SD	mean	SD	mean	SD	mean	SD
1	31.3	6.4	17.5	1.5	42.6	7.6	42.3	10.4
2	34.6	6.9	33.6	10.1	55.2	7.5	53.0	13.9
3	43.8	7.2	38.6	10.8	71.3	12.4	64.3	15.1
4	43.5	7.7	25.7	11.3	47.6	14.7	29.3	10.0
5	58.3	17.1	50.8	11.5	94.1	11.2	30.0	24.2
6	51.6	8.8	31.8	8.2	99.1	27.6	53.6	13.6
7	87.5	12.9	54.9	9.7	63.2	8.5	76.2	16.6
8	37.6	8.8	31.9	3.1	66.2	15.2	52.8	13.5
mean	48.5	9.5	35.6	8.3	67.4	13.1	50.2	14.7
SD	16.9	3.4	11.6	3.6	19.1	6.2	15.0	4.2

experimental conditions

As indicated by Table 9.5, T_{re}, $\bar{T}_{sk}$ and body heat content were significantly different between the warm and cool body core condition. In subject 4, however, the difference between the warm and cool body core condition was minimal.

hunting-parameters

Table 9.5 shows that almost all hunting parameters were significantly different between the cold and very cold water conditions and the warm and cool body core conditions. Fig. 9.3 summarizes the results.

An increased body temperature is related to higher finger skin temperatures, increased heat transfer of the hands to the water, higher T_{min} and T_{max}, shorter onset times to CIVD, increased CIVD amplitude, less pain and more comfortable temperature sensation.

Immersion of the hands in colder water is related to lower finger skin temperatures, increased heat transfer from the hands to the water (the temperature gradient between the hands and the water increased), lower T_{min} and T_{max}, increased CIVD amplitude, more pain and less comfortable temperature sensations.

None of the investigated hunting parameters showed interaction between body temperature and water bath temperature, with the exception of the PCC. When the body was warm and the water not very cold, the hunting reaction of the fingers in one hand were rather similar, as indicated by a high PCC. Fig. 9.4 shows the PCC for the experimental conditions and for the different finger combinations.

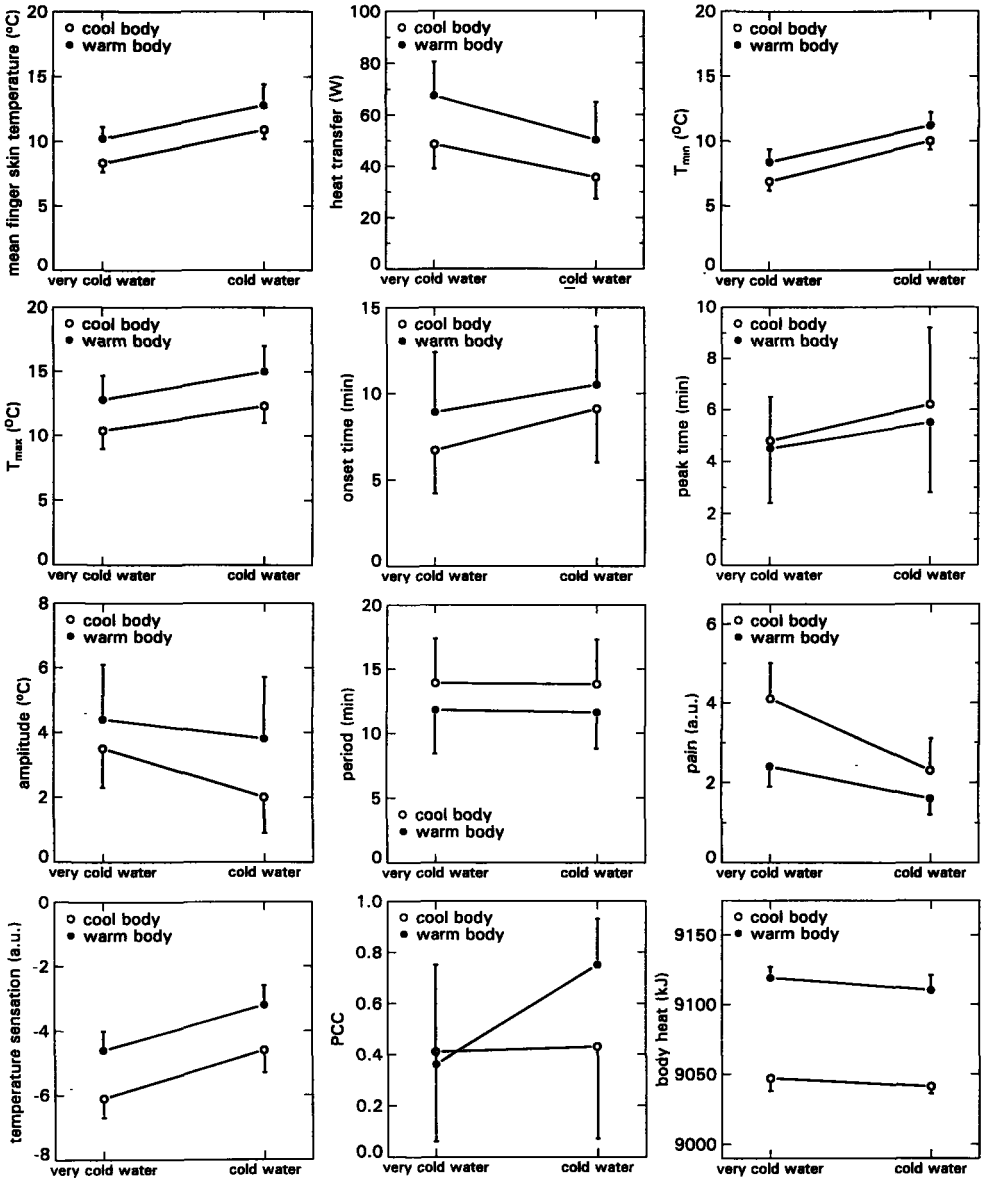

Fig. 9.3 Mean finger skin temperature (°C), hand heat transfer (W), T_{min} (°C), T_{max} (°C), onset time (min), peak time (min), amplitude (°C), period (min), pain score (arbitrary units), temperature sensation (arbitrary units), Pearson correlation coefficients (PCC) and body heat (kJ), averaged over all subjects for the four experimental conditions. The vertical bars denote the mean SD within subjects.

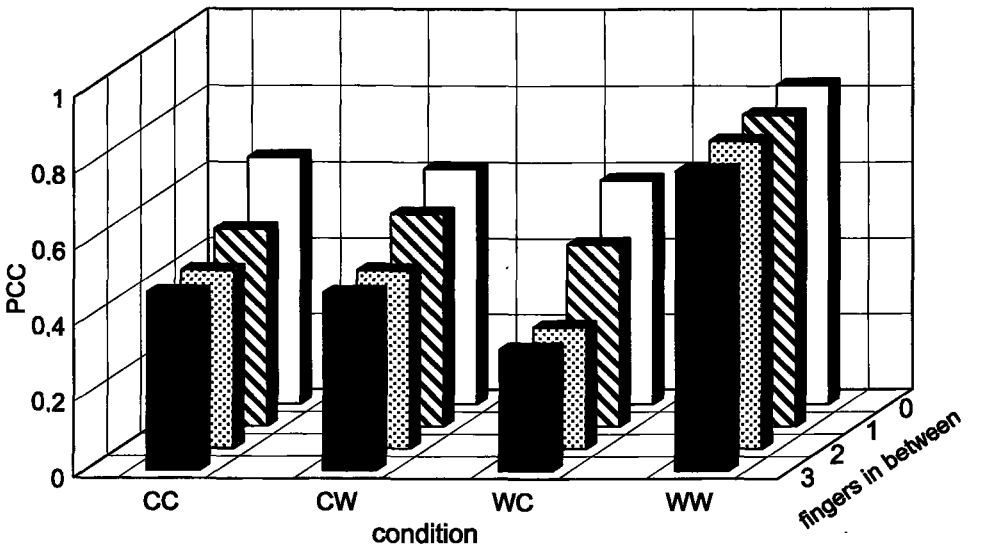

Fig. 9.4 Pearson correlation coefficients (PCC) between fingers for the experimental conditions, indicating from back to front the number of fingers in between. CC = cool core & very cold water; CW = cool core & relatively warm water; WC = warm core & very cold water; WW = warm core & relatively warm water.

The PCC differed according to the number of fingers that separated them (see previous chapters). The PCC's, averaged over the experimental conditions, were 0.68, 0.60, 0.52 and 0.51 for 0, 1, 2 and 3 fingers in between, respectively. The PCC between the fingers of both hands was 0.34. The fingers with partly shared innervation had higher (0.73 versus 0.62) correlations, but this was not significant (Kruskal-Wallis test, $P>0.05$).

relation between threshold and hunting parameters

The difference between the obtained T_{es} during the immersion experiments and the thresholds in T_{es} (Table 9.4) was calculated. This difference was not significantly related to any hunting parameter. This means that incorporation of the subject specific esophageal threshold above which the hand blood flow increases, does not explain the behaviour of the hunting parameters.

pain and thermal sensation

The experienced pain was less when the body core and the water were relatively warmer. Also, there was more thermal comfort when the water and body core were relatively warm.

9.4 Discussion

interindividual differences

In the previous chapter it was shown that the hunting reaction differed vastly between subjects. It was suggested that an individual threshold in core temperature for cold induced vasodilation (CIVD) might exist, similar to the threshold for finger blood flow shown in chapter 5. In that chapter the fingers were only mildly cooled in water of 15 to 25°C, where CIVD normally does not occur.

To verify the hypothesis that the same threshold is also of importance for CIVD, the threshold in core temperature for finger blood flow was determined prior to the immersion experiments in cold water.

The results do not support the hypothesis: the difference between the actual T_{es} and the threshold was not related to hunting parameters. In the experimental conditions of chapter 5 the main determinant of the finger blood flow was the temperature of the body core. The cold pain nerve endings were not activated by the water temperature of 15 to 25°C. In this experiment, however, a stronger peripheral drive due to the low water temperature was present, which apparently has a strong influence on the hunting parameters.

effect of core temperature

The relatively short periods of cooling and warming allowed the entire experiment to take place within a few hours, so that the esophageal and rectal probe could stay in the same place. Consequently, the short time intervals between the immersion periods resulted only in small changes in the core temperature, mean skin temperature and body heat content of the subjects. However, despite the small differences in core temperature, mean skin temperature and body heat content (Table 9.5), most hunting parameters were significantly different. This stresses the sensibility of the hunting reaction for central sympathetic activity. This is in agreement with previous investigations, as outlined in Table 2.1.

The high PCC values in the condition with the highest core and water bath temperature shows that the temperature fluctuations of the immersed fingers are rather similar. This is in agreement with the increased central control at high core temperatures.

effect of water temperature

Blaisdell (1951) showed that CIVD in the fingers occurred even when the subjects were considerably chilled (two hours nude in a 12°C room). However, the CIVD was only seen when the fingers were sufficiently cooled. In this experiment the hunting reaction was found in all experimental conditions.

The water temperature affected the hunting reaction in a clear manner: the finger skin temperatures were lower, heat transfer from the hands to the water increased, the CIVD amplitude increased and more pain and less comfortable temperature sensations were reported.

Although T_{min} was lower, the time to reach this minimum (onset time) tended to be slightly shorter for the very cold water than for the cold water. In contrast with the findings of Kramer and Schulze (1948), the period was not dependent on the temperature of the surrounding medium.

pain and thermal sensation

The results show that the experienced pain and thermal sensation was less when the core and the water were relatively warm. Considering the small differences between the experimental conditions, these subjective parameters can be considered as sensitive. Pain (and thermal sensation) are supposed to be related to the vasoconstrictor activity during the hunting reaction (par. 2.3.2).

9.5 Summary

In eight subjects the esophageal threshold for finger vasodilation was related to the hunting reaction. After determination of the threshold, the subjects immersed their hands four times: in 5 and 8.5°C water with a slightly cooled and also with an elevated body core temperature.

Even when the body heat content was mildly elevated, the characteristics of the hunting reaction showed significant changes. An increased body temperature was related to higher finger skin temperatures, increased heat transfer of the hands to the water, higher T_{min} and T_{max}, shorter onset times to cold induced vasodilation (CIVD), increased CIVD amplitude, less pain and more comfortable temperature sensation.

Immersion of the hands in colder water was related to lower finger skin temperatures, increased heat transfer from the hands to the water, lower T_{min} and T_{max}, increased CIVD amplitude, more pain and less comfortable temperature sensations. The individual esophageal threshold for finger vasodilation was not related to the hunting parameters. This indicates that the local cold stimulus has a strong impact on the CIVD response.

Chapter 10*

The effect of body core temperature and mean skin temperature on the hunting reaction of the fingers

10.1 Introduction

Lewis (1930) was the first author to describe the hunting reaction that occurs during exposure of the fingers to cold, the ascending part of which is commonly referred to as a cold induced vasodilation (CIVD). He noted, however, that the CIVD reaction in the fingers often failed to occur when the subjects were exposed to low ambient temperatures prior to immersion. Later, Spealman (1945) investigated the effect of exposing the body to different ambient temperatures on hand blood flow. One hand was immersed in water between 2 and 35°C, while the rest of the body was exposed to three environmental conditions which made the subjects uncomfortably warm, comfortable or uncomfortably cool but not shivering. At any given water temperature, hand blood flow was greater when the body felt warmer. Furthermore, the hunting reaction was reduced when the body felt cold. Later, several studies supported the observation that ambient temperature had an impact on the hunting reaction. These studies showed that exposing the body to a high ambient temperature during cold finger stress, induced an increased finger or hand blood flow during the hunting reaction (Bader and Mead, 1949; Edwards and Burton, 1960; Folkow et al., 1963; Keatinge, 1957; Spealman, 1945), a higher finger skin temperature (Blaisdell, 1951; Kramer and Schulze, 1948; Werner, 1977; Yoshimura and Iida, 1950), an increased heat transfer to the surrounding medium (Elsner et al., 1960; Greenfield et al., 1951) and a faster onset of the hunting reaction (Adams and Smith, 1962; Tanaka, 1971; Yoshimura and Iida, 1950).

Although the ambient temperature varied and the thermal comfort changed in the above cited experiments, no evidence was provided that the observed differences in the hunting reaction were the result of a changed core temperature (T_c) or a changed mean skin temperature ($\bar{T}_{sk}$). The purpose of the present study was to try to quantify the relation between T_c / $\bar{T}_{sk}$ and the characteristics of the hunting reaction for the finger immersed in cold water.

*This study is accepted for publication by Eur. J. Appl. Physiol.

10.2 Material and methods

subjects

Nine healthy Caucasian male subjects, whose ages ranged from 19 to 34, volunteered for the study. They were accustomed to cold water exposure of the extremities, either from their profession as a diver or from participation in similar studies. The subjects were visually checked for a healthy tympanum by a medical doctor. All subjects were informed of the details, discomforts and risks associated with the experimental protocol and had been granted medical approval, before they signed a written consent. The protocol was approved by the Human Ethics Committee of the Defence and Civil Institute of Environmental Medicine.

instrumentation

$\bar{T}_{sk}$ was determined by eight thermistors of 1 cm in diameter (Yellow Springs Instruments, 400 series), taped to the skin with one layer of thin tape at the pad of the left and right middle finger, forehead, back, chest, upper arm, thigh and foot. A thin latex surgical glove was worn over the sensors on the hand that had to be immersed. Rectal temperature (T_{re}) was measured with a Baxter Pharmaseal 400 probe inserted 12 cm beyond the anal sphincter. Ear canal temperature (T_{ear}) was measured by a Baxter Pharmaseal 400 series rectal/esophageal probe, in which the plastic cover was replaced by a silicon tubing. A knot was made near the end of the probe and the knot was fitted tightly in the ear canal. The subjects positioned the end of the probe close to the tympanic membrane, central in the ear canal. After touching the tympanic membrane, the probe was withdrawn just enough for the pain sensation to disappear. Hereafter, the external ear was insulated with a cotton ball and head phones.

All temperatures, including the water bath temperature and the ambient temperature were continuously recorded using an automated data acquisition system (Hewlett Packard 85 computer, 3974A scanner/voltmeter) with minute averages calculated and stored for further analysis.

protocol

There were three main body temperature conditions: warm, neutral and cool. The *warm* body temperature was induced by exposing the subjects to an ambient temperature of 30°C. The subjects were wearing socks, shoes and a sweat shirt and a pair of trousers over shorts and T-shirt. The *neutral* test (called Nn) was performed in a climatic chamber of 22°C after drinking a 750 ml beverage (water with added ice tea powder containing mainly sugar) at 37°C. The subjects were wearing shorts, T-shirt, socks and shoes. The *cool* body temperature was induced by an ambient temperature of 15°C. The subjects wore a swimsuit only.

In the warm and cool conditions the subjects were asked to drink 750 ml of either cold (0°C) or hot (42-44°C) ice tea beverage. The test in the warm chamber with the cold drink is called Wc and that with the hot drink is called Wh. In the cool chamber the codes are Cc and Ch respectively. The beverage was used to vary the core temperature (T_c) while the ambient temperature was used to vary $\bar{T}_{sk}$.

In the climatic chamber the relative humidity was about 50% for all air temperatures. The horizontal air velocity did not exceed 0.2 m/s.

The order of the sessions was balanced with the neutral session serving as a control. Each test was performed at the same time of the day for a specific subject with a minimum of 48 hours between two exposures.

After being instrumented with the skin thermistors and the rectal and ear canal probes, the subjects entered the climatic chamber at a preselected temperature, sat on a chair and waited for stabilization of T_{ear} to baseline level (= $T_{ear,base}$), which took about 20 to 30 minutes. Then, the subjects ingested the beverage within a 5 minute period. As the induced change in T_{ear} started to level off (about 15 to 20 minutes after the drink), the dominant hand was immersed to the wrist in a temperature controlled water bath set at 8 °C ± 0.5 °C (Haake, Berlin) for 30 minutes. The bath was located at the level of the heart and was vigorously stirred by a jet pump. In order to maintain the elevated or lowered T_{ear}, up to 400 ml of hot or cold beverage was given to the subjects during the immersion. Following the cold water immersion, the hand was withdrawn from the bath and the surgical glove was removed. The hand was then held freely in the ambient air to allow for monitoring of rewarming. The total duration of the test was less than two hours.

Calculations

Mean skin temperature of the body ($\bar{T}_{sk}$) was calculated according to Hardy and Dubois (1938) with the mean of the left and right finger skin temperature taken as a substitute for hand temperature. $\bar{T}_{sk}$, T_{ear} and T_{re} were averaged over the immersion period and denoted by $\bar{T}_{sk,imm}$, $T_{ear,imm}$ and $T_{re,imm}$ respectively. The following descriptors of the finger hunting reaction were determined: baseline finger pad temperature just prior to immersion ($T_{fi,base}$); time to the first rise in temperature after immersion (onset time); minimum recorded temperature ($T_{fi,min}$); maximum recorded temperature after the first minimum ($T_{fi,max}$); the largest recorded temperature amplitude (ΔT_{fi}); and the number of waves (N_{waves}, rounded to whole numbers for every subject) during the 30 minute immersion period. In some subjects a plateau in finger skin temperature may occur immediately after immersion. In this case, onset time, N_{waves} and ΔT_{fi} are calculated with reference to the start of the drop following this plateau. The area between the finger skin temperature curve and the 8 °C water bath temperature baseline during the 30 minute immersion period (AREA) was calculated using a digitization tablet attached to a Hewlett Packard computer. The area has been previously shown to be a good estimator of the heat loss by the fingers during immersion (Hsieh et al. 1965).

Statistical analysis

A two way analysis of variance was performed with treatment (beverage, ambient temperature) and subjects as independent variables. If main effects were found for a particular independent variable, all combinations were then analysed by post-hoc analysis (SYSTAT, module MGLH - CONTRAST). Significance was accepted at the level of $p < 0.05$. Multiple linear regression was performed using the least square criterion, with the order of the independent variables entering the

equation determined by the correlation coefficient. All mean values are given with the standard error of the mean (SEM).

10.3 Results

core temperature

The mean values of $T_{ear,base}$ were 0.02 to 0.65°C (mean: 0.33 ± 0.03°C) lower than $T_{re,base}$. Table 10.1 shows that the ingestion of hot or cold beverage caused significant changes in both T_{ear} and T_{re}. With thermoneutral ingestion there was no change in these core temperature measures. The hot beverage caused an increase in T_{ear} and T_{re}. The cold beverage decreased T_{ear} and T_{re}.

Table 10.1 Effect of beverage temperature on core temperature. All core temperatures are given with the SEM.

	Beverage temperature					
	Neutral (37°C) (condition Nn)		Hot (43°C) (conditions Wh&Ch)		Cold (0°C) (conditions Wc&Cc)	
	T_{ear}	T_{re}	T_{ear}	T_{re}	T_{ear}	T_{re}
Before drinking (°C)	36.79 ± 0.09	37.20 ± 0.08	36.86 ± 0.06	37.16 ± 0.06	36.86 ± 0.06	37.20 ± 0.06
After drinking (°C)	36.83 ± 0.09	37.19 ± 0.08	37.15 ± 0.06	37.25 ± 0.06	36.52 ± 0.10	36.99 ± 0.07
Temperature change (°C)	0.03 ± 0.01	-0.01 ± 0.01	0.29 ± 0.03*	0.09 ± 0.03*	-0.34 ± 0.08*	-0.21 ± 0.02*

* = significant different before and after drinking (paired t-test ($p<0.01$))

In the warmest condition (Wh), the raised T_{ear} could not be fully maintained, probably because of the induced sweating response. However, additional drinking of up to 400 ml hot beverage limited the drop of T_{ear} to about 0.1°C during the 30 minute immersion period. Lowered core temperatures could be maintained with only minimal drinking during the immersion period, even though all subjects were shivering during the coldest condition (Cc). Figure 10.1 shows the body temperatures at baseline level, just prior to the hand immersion and just prior to withdrawal of the hand from the water bath.

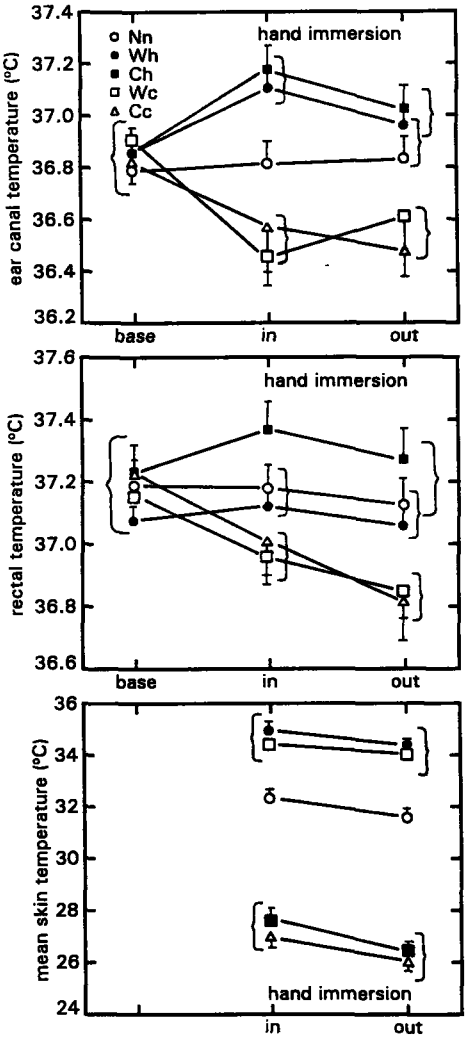

Fig. 10.1 Core and mean skin temperatures (±SEM) observed before and during the hand immersion tests for the five different experimental conditions (n=9). The baseline $\bar{T}_{sk}$ was not measured since it was not controlled by the protocol. The values that were not statistically different are grouped by parenthesis.

Mean skin temperature of the body

$\bar{T}_{sk}$ was not different between the hot drink and cold drink conditions (conditions Wh versus Wc and Ch versus Cc), which indicates that the temperature of the beverage did not influence the $\bar{T}_{sk}$. During the hand immersion, $\bar{T}_{sk}$ decreased insignificantly (Fig.10.1). The mean values of $\bar{T}_{sk}$ were 26.8 ± 0.3°C in the cool chamber, 32.0 ± 0.3°C in the neutral chamber and 34.4 ± 0.2°C in the warm chamber. Mean values of $\bar{T}_{sk}$ are shown in Figure 10.1 at the start and termination of the hand immersion.

Hunting reaction

In Table 10.2 the mean values of the descriptors of the hunting reaction are shown with the standard error of the mean (SEM) for every experimental condition. The highest finger skin temperatures and area and the shortest onset time were found for the Wh conditions, followed by Wc, Nn, Ch and Cc respectively. In condition Wh, all subjects showed an initial plateau of the finger skin temperature around 20°C. The largest number of waves were found for the Wh condition followed by Nn, Wc, Ch and Cc respectively. Contrast analysis revealed that all variables but $T_{fi,base}$ differed between Wh and Nn, and that all variables but ΔT_{fi} differed between Nn and Cc. Interindividual variability remained evident, even under these thermally standardized conditions, as is shown by the SEM in Table 10.2.

Table 10.2 Mean values and standard error of the mean (SEM) of various descriptors of the hunting reaction, as defined in Fig. 3.1. For each descriptor three statistically different groups were found. These groups are indicated by normal typeface, dark background and bold typeface respectively. Within each group the differences are not statistically different.

Climatic Chamber	Warm	Warm	Neutral	Cool	Cool
Beverage	hot	cold	neutral	hot	cold
Code	Wh	Wc	Nn	Ch	Cc
AREA (°C·min)	240 ±31	135 ±14	118 ±14	113 ±21	**49 ±7**
$T_{fi,base}$ (°C)	35.3 ± 0.4	33.5 ± 0.3	32.1 ± 1.0	27.9 ± 2.3	**19.3 ± 0.9**
onset time (min)	3.0 ± 0.9	10.7 ± 2.6	10.6 ± 2.0	**17.0 ± 2.7**	**18.9 ± 3.0**
$T_{fi,min}$ (°C)	11.3 ± 0.5	9.8 ± 0.3	9.6 ± 0.3	9.4 ± 0.4	**8.7 ± 0.2**
$T_{fi,max}$ (°C)	17.0 ± 1.8	13.0 ± 0.8	12.6 ± 0.8	**10.7 ± 0.6**	**9.5 ± 0.4**
ΔT_{fi} (°C)	5.9 ± 1.6	3.3 ± 0.6	**3.0 ± 0.6**	**1.2 ± 0.3**	**0.8 ± 0.2**
N_{waves}	2.6 ± 0.4	**1.2 ± 0.2**	1.6 ± 0.2	**1.0 ± 0.2**	**0.8 ± 0.2**

The hunting reaction for conditions Wh, Nn and Cc is visualized in Figure 10.2, based on the parameters shown in Table 10.2.

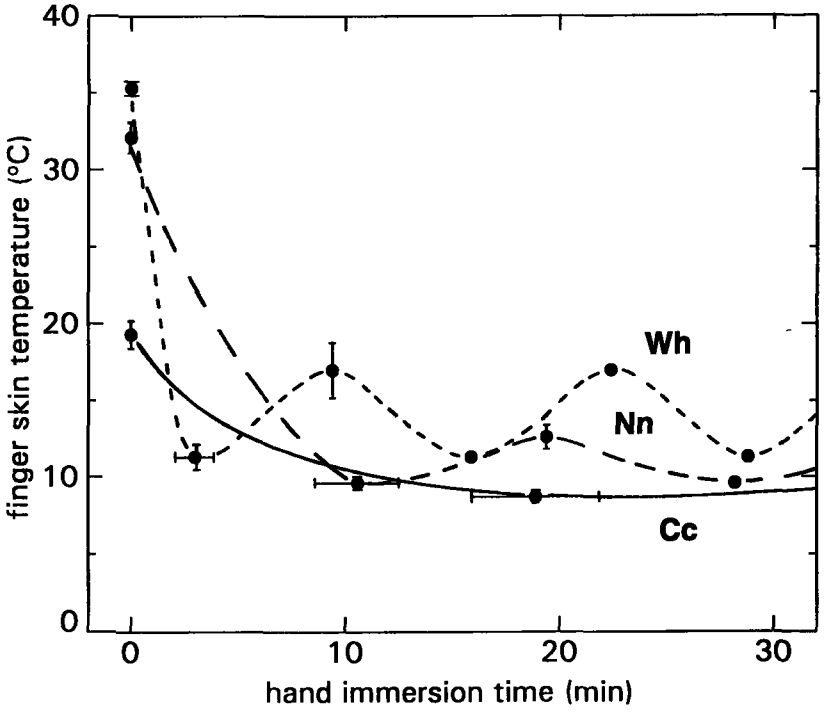

Fig. 10.2 Typical hunting reaction of a middle finger immersed in 8 °C water for the warmest (Wh), coldest (Cc) and neutral (Nn) condition as reconstructed from an average response from the nine subjects.

The relation between AREA and both core temperature and mean skin temperature was quantified by multiple regression analysis. Best predictors for changes in AREA were $\Delta T_{ear,imm}$ ($T_{ear,imm}$ - $T_{ear,base}$) and $\Delta \bar{T}_{sk,imm}$ ($\bar{T}_{sk,imm}$ - 32.2), where 32.2 °C represents the $\bar{T}_{sk}$ during the immersion period for the neutral condition. The regression equation is as follows:

$$\text{AREA (°C·min)} = 79.0\ \Delta T_{ear,imm} + 15.1\ \Delta \bar{T}_{sk,imm} + 146.5 \qquad [10.1]$$

with a multiple correlation coefficient of 0.71. This means that the heat transfer of the middle finger during cold immersion is relatively more influenced by changes in T_c (i.e. $\Delta T_{ear,imm}$) than by changes in $\bar{T}_{sk}$.

10.4 Discussion

It was shown previously that the timing and magnitude of the hunting reaction was dependent upon ambient temperature, but the actual core and skin temperatures were not measured or reported adequately. The results of the present study show that the hunting pattern is in part determined by body temperatures. When the body core and skin were warmest (condition Wh), the heat transfer (as assessed by area under the finger skin temperature curve), $T_{fi,min}$, $T_{fi,max}$ and ΔT_{fi} were highest with a corresponding short onset time and high hunting frequency. When the body core and skin were coolest (condition Cc), the heat transfer and finger skin temperatures were the lowest of all experimental conditions. Moreover, it took almost 19 minutes before CIVD occurred and the hunting frequency was low. The heat transfer was almost five times higher in condition Wh as compared to condition Cc.

Blaisdell (1951) exposed the subjects for 2 to 3 hours to an ambient temperature of 12 to 15°C and found no decrease in T_{re}, due to the increased metabolism by shivering. It is likely that the one hour exposure of minimally dressed subjects to an ambient temperature of 7°C (Adams and Smith, 1962) or 5 - 6°C (Keatinge, 1957) also was insufficient to cause a significant decrease in body core temperature. However, changes in hunting parameters are found in all investigations. This indicates that $\bar{T}_{sk}$ is probably an important determinant of the hunting reaction.

The relative contribution of $\bar{T}_{sk}$ and T_c to the hunting parameters was investigated by comparison of condition Wc to Nn (decrease in $\bar{T}_{sk}$ and increase in T_c) and Ch to Nn (increase in $\bar{T}_{sk}$ and decrease in T_c). In condition Wc the hunting reaction was not significantly different from the thermoneutral condition (Nn), as can be seen in Table 10.2. The reduced core temperature thus counterbalanced the effect of the increased $\bar{T}_{sk}$ on the hunting reaction. Fig. 10.1 indicates that T_{ear} is 0.33°C less and $\bar{T}_{sk}$ is 2.2°C higher in condition Wc as compared to Nn. Thus, the ratio of $\Delta\bar{T}_{sk}$ over ΔT_c is 6.7. This supports formula [10.1] where the increase in $\bar{T}_{sk}$ has to be 5.2 times higher than the increase in T_c in order to have the same effect on AREA.

In condition Ch the T_{ear} was 0.27°C higher and $\bar{T}_{sk}$ was 5.0°C less as compared to condition Nn. The ratio of $\Delta\bar{T}_{sk}$ over ΔT_c is more than 18, and this is about three times higher than the ratio found in the comparison of condition Wc to Nn, to obtain good counterbalance of $\bar{T}_{sk}$ and T_c on the hunting parameters. Thus, $\bar{T}_{sk}$ has a strong impact on the onset time of CIVD. As a result, the onset time and the number of waves were different in condition Ch as compared to Nn. The onset time is much longer when the climatic chamber temperature and $\bar{T}_{sk}$ are low (Table 10.2).

In this study, both $\bar{T}_{sk}$ and T_c are shown to have a potent influence on the hunting reaction. The information from the skin and core serve as inputs for the vasomotor centre in the central nervous system. This centre determines the vasomotor status in the fingers by modifying the sympathetic output to the peripheral nerves. When the core and skin are cool the sympathetic output increases and peripheral vasoconstriction results. The hunting reaction seems to superimpose upon the general vascular status of the peripheral blood vessels.

It is important to consider that the changes in finger skin temperatures occur later than changes in finger blood flow (Nilsson et al., 1986). However, the finger skin temperature gives an overall impression of the thermal changes in the finger tip.

The changes in T_c due to the drinking of the beverages are both seen in the ear canal and in the rectum. It is possible that the ingestion of the fluid caused reflex thermoregulatory effects (Goldman et al., 1973). However, the ingestion of the hot beverage caused no decrease in $\bar{T}_{sk}$, so that the thermoregulatory effects of drinking the beverages are likely to be minimal. The induced changes in T_c and $\bar{T}_{sk}$ in this study are small, and more research is needed to investigate the hunting reaction in hyperthermia and in particular in hypothermia. This is important since the protective properties of the hunting reaction for the prevention of local cold injuries (e.g., Iida, 1949) are most relevant in hypothermic conditions.

We suggest that the ingestion of warm fluids prior to work in the cold may raise the core temperature sufficiently to cause a slowing of the finger skin cooling, thus prolonging the ability to carry out manual work requiring dexterity in the cold.

In conclusion, this study shows that a slightly elevated core temperature and mean skin temperature enhances the hunting reaction. The minimal and maximal finger skin temperatures during immersion in cold water are higher when the body core temperature is elevated; $\bar{T}_{sk}$ seems to have the strongest impact on the onset time of CIVD.

10.5 Summary

The relationship between body temperature and the hunting reaction (intermittent supply of warm blood to cold exposed extremities) was quantified for nine subjects by immersing one hand in 8°C water while their body was warm, cool or comfortable. Core and skin temperatures were manipulated by exposing the subjects to different ambient temperatures (30, 22, 15°C), by adjusting their clothing insulation (moderate, light, none), and by drinking beverages at different temperatures (43, 37 and 0°C). The middle finger temperature response was recorded (T_{fi}), together with ear canal (T_{ear}), rectal (T_{re}), and mean skin temperature ($\bar{T}_{sk}$). The induced mean T_{ear} changes were -0.34 ± 0.08 and +0.29 ± 0.03°C for the cold and hot beverage respectively. $\bar{T}_{sk}$ ranged from 26.7 to 34.5°C during the tests. In the **warm environment** after a hot drink, the initial finger temperature ($T_{fi,base}$) was 35.3 ± 0.4°C, the minimum finger temperature during immersion ($T_{fi,min}$) was 11.3 ± 0.5°C and 2.6 ± 0.4 hunting waves occurred in the 30 minute immersion period. In the **neutral condition** (thermoneutral room and beverage) $T_{fi,base}$ was 32.1 ± 1.0°C, $T_{fi,min}$ was 9.6 ± 0.3°C and 1.6 ± 0.2 waves occurred. In the **cold environment** after a cold drink, these values were 19.3 ± 0.9°C, 8.7 ± 0.2°C and 0.8 ± 0.2 waves respectively. A colder body induced a decrease in magnitude and frequency of the hunting reaction. The total heat transferred from the hand to the water, as estimated by the area under the middle finger temperature curve, was also dependent upon the induced increase or decrease in T_{ear} and $\bar{T}_{sk}$. We conclude that the characteristics of the hunting temperature response curve of the finger are in part determined by core temperature and mean skin temperature. T_{min} and T_{max} were higher when the core temperature was elevated; $\bar{T}_{sk}$ seemed to be an important determinant of the onset time of the cold induced vasodilation response.

Chapter 11

Intra-individual differences in the hunting reaction

11.1 Introduction

The present study will investigate the reproducibility of the hunting reaction by comparing the skin perfusion and finger skin temperatures of eight subjects, who immersed their hands in cold water on three different days at the same time of day.
As far as we know, the reproducibility of the hunting reaction has only been investigated by Meehan (1955). Two subjects were investigated on five separate days and two subjects on six separate days. The mean temperature during the last 25 minutes of immersion was reproduced within about 0.5°C for a subject and the minimum temperature within about 1°C. However, no data is available on the time aspects of the hunting reaction. Yoshimura and Iida (1952) investigated the reproducibility of the Frostbite Reaction Index, a derivative from both amplitude and time parameters of the hunting reaction. In five subjects the index was determined every 2 to 4 days for about a month under the same experimental conditions. The maximum variation was ± 1 point which is a relatively high reproducibility. The Frostbite Reaction Index, however, does not give information on the re producibility of specific hunting parameters. Therefore, the information on reproducibility of the hunting reaction is limited.

Another aspect of this study concerns the comparison of finger temperature recordings and Doppler flowmetry. The recently developed Doppler technique is an estimator of local skin blood flow with a limited pick up volume of less than 1 mm^3 (see par. 3.2). Finger skin temperature is also used as an indicator for skin blood flow, although it is the resultant of the finger heat balance and affected by several parameters, such as the temperature and conductivity of the surrounding medium. Finger skin temperature is indicative for a much larger tissue area than laser Doppler flowmetry. Most recent publications use Doppler flowmetry to assess skin blood flow, older publications used skin temperature measurements (e.g., Lewis, 1930). In order to bridge the gap, a comparison between Doppler flowmetry and finger skin temperatures has been included in this experiment.

11.2 Material and methods

subjects
Eight male subjects participated in the study. Their relevant anthropometric data are presented in Table 11.1.

Table 11.1 Anthropometric characteristics of the subjects.

subject	age	weight	stature	body surface area	palmar surface area		hand volume	
	years	kg	cm	m^2	cm^2		cm^3	
					left	right	left	right
1	19	78	192	2.07	190	199	503	534
2	20	87	195	2.19	196	196	558	588
3	22	80	180	2.00	180	192	533	556
4	25	75	177	1.92	146	156	358	375
5	18	62	183	1.81	172	175	470	485
6	27	71	183	1.92	152	161	424	426
7	18	75	181	1.95	162	165	380	394
8	18	65	175	1.79	159	159	413	430
mean	21	74	183	1.96	170	175	455	474
SD	3	8	7	0.13	18	18	73	79

methods

The laser Doppler probe was attached to the right middle finger (par. 3.2).

Every finger was equipped with a thermocouple (par. 3.3.1). On the distal volar end of the right middle finger two thermocouples were placed a few mm from the Doppler beam end. The response time of two differently sized thermocouples were tested during the hunting reaction. Both thermocouples were Type T (copper/constantan). The thin thermocouple had a core diameter of 0.3 mm, the other had a diameter of 0.5 mm. The junctions were sealed by PVC, which resulted in diameters of about 1.2 mm and 3.2 mm respectively.

Three thermocouples were used to calculate $\bar{T}_{sk}$ (par. 3.3.2). During the experiments the rectal temperature of the subjects was measured (par. 3.3). The body heat content was calculated according to par. 3.3.4.

The heat transfer of the immersed hand(s) was determined by calorimetry (par. 3.5).

Every 5 minutes during the immersion period the subjects were asked to rate the pain and temperature sensation (par. 3.6).

procedure
Each subject participated in the experiment on three different days with at least a two days interval between the trials. The hands were immersed in 6°C water at 9.30 hours for subjects 1 and 5, 11.30 h. for subjects 2 and 6, 13.30 h. for subjects 3 and 7 and 15.30 h. for subjects 4 and 8.

After the instrumentation of the subjects, they entered the climatic chamber where they had to sit quietly for one hour until the moment of immersion. The temperature in the climatic chamber was about 26°C with about 40% relative humidity. The right hand was immersed first in the water bath of about 6°C, followed by the left hand two minutes later. This procedure enabled the investigation of the occurrence of synchronization during the immersion period.
The hands were withdrawn 40 minutes after the immersion of the right hand. During the immersion the subject was seated on a chair with his chest against the back-rest. The hands were hanging down in a calorimeter water bath with the backs of the wrists touching each other.
The subjects were lightly dressed in a shirt and pants.

data processing
The signals from the thermocouples, thermistors, and flow meter and thermopile of the calorimeter were sampled every 10 seconds.

11.3 Results

reproducibility
In Fig. 11.1 an example is given of the data for subject 5 for the three sessions.

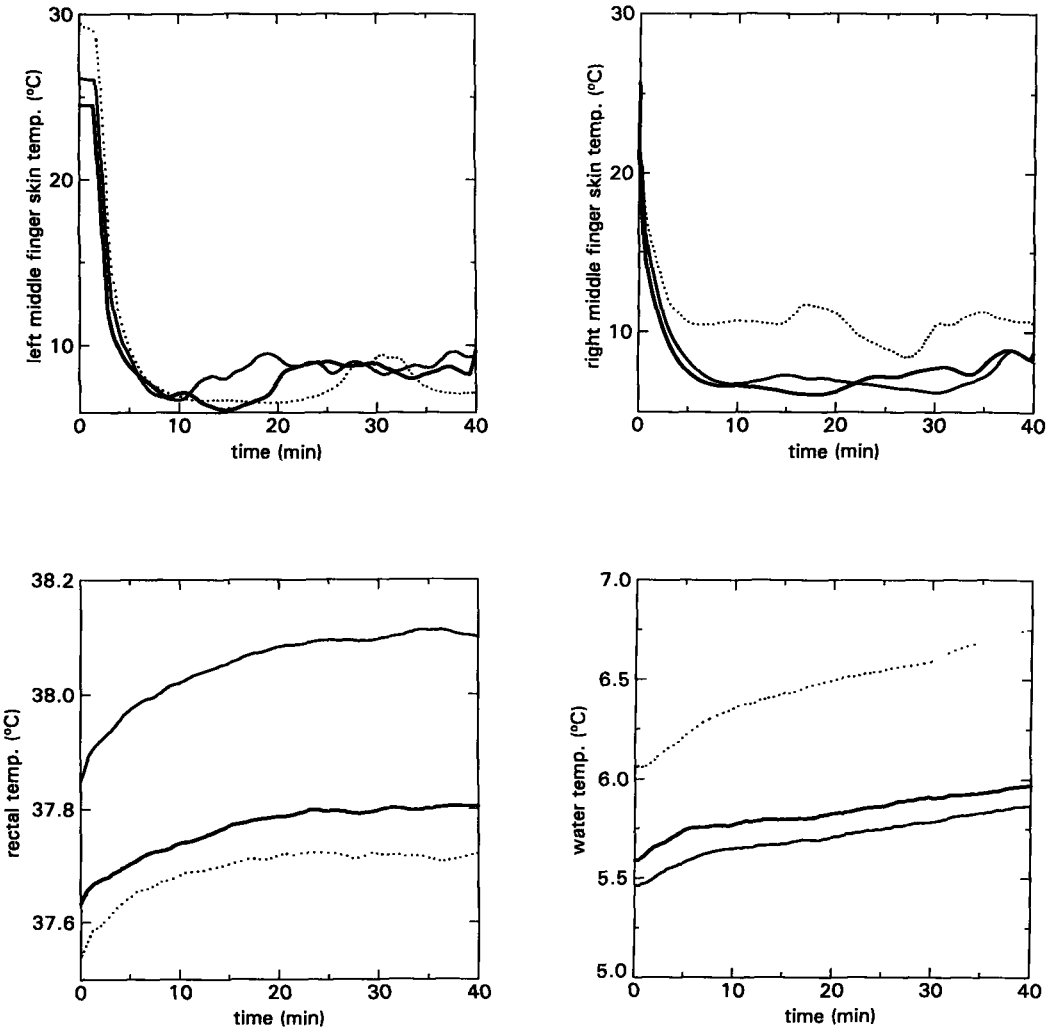

Fig. 11.1a Left and right middle finger skin temperature (°C), rectal temperature (°C), and water bath temperature (°C) for a typical subject (subject 5). Each curve represents one trial.

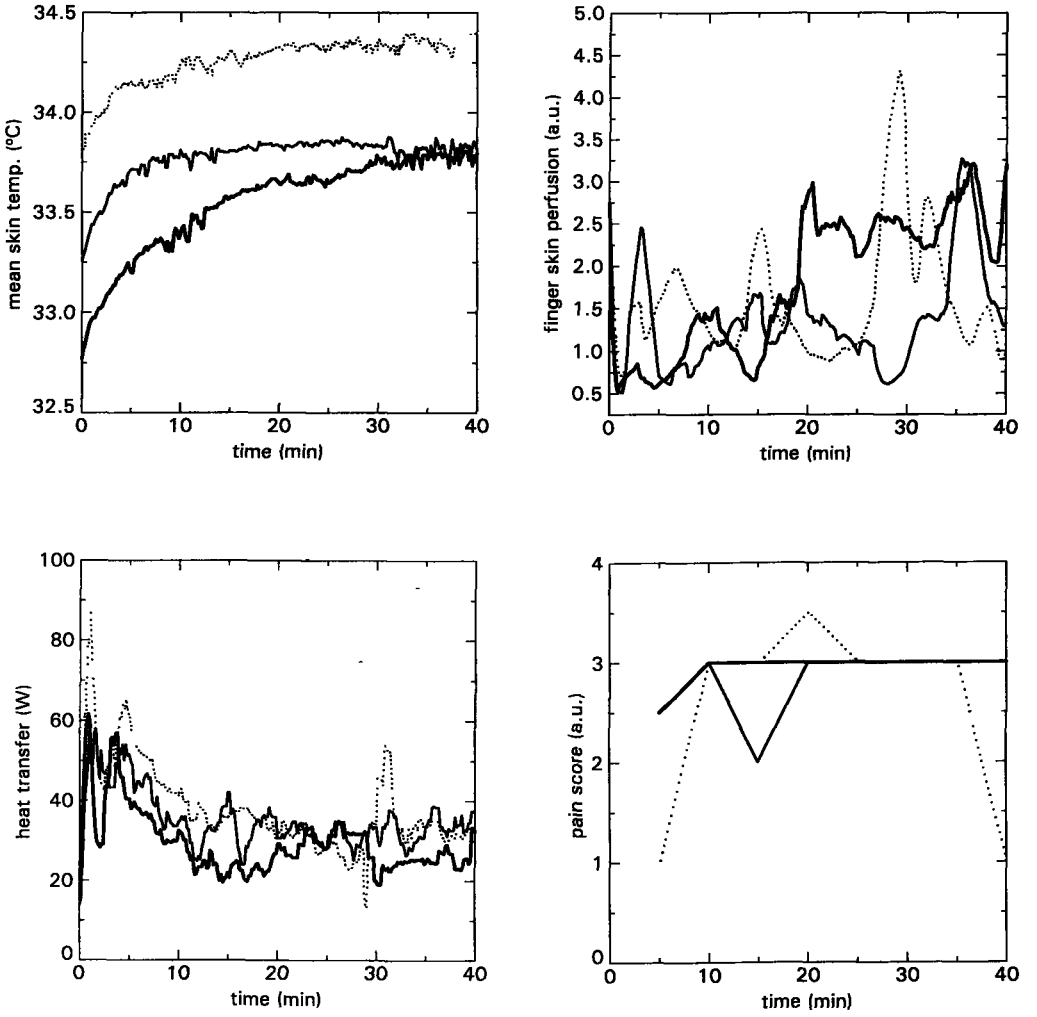

Fig. 11.1b Mean (body) skin temperature (°C), laser Doppler blood flow of the right middle finger (a.u.), heat transfer (W) and pain rating for a typical subject (subject 5). Each curve represents one trial.

The rectal temperature and mean skin temperature generally increased during the immersion phase, despite the heat loss of about 35 W from the hands to the water bath.

In Fig. 11.2 the body heat content, mean finger skin temperatures of the left and right hand, hand heat transfer and T_{min} are shown for every experiment and subject, averaged over the 10th to 38th minute.

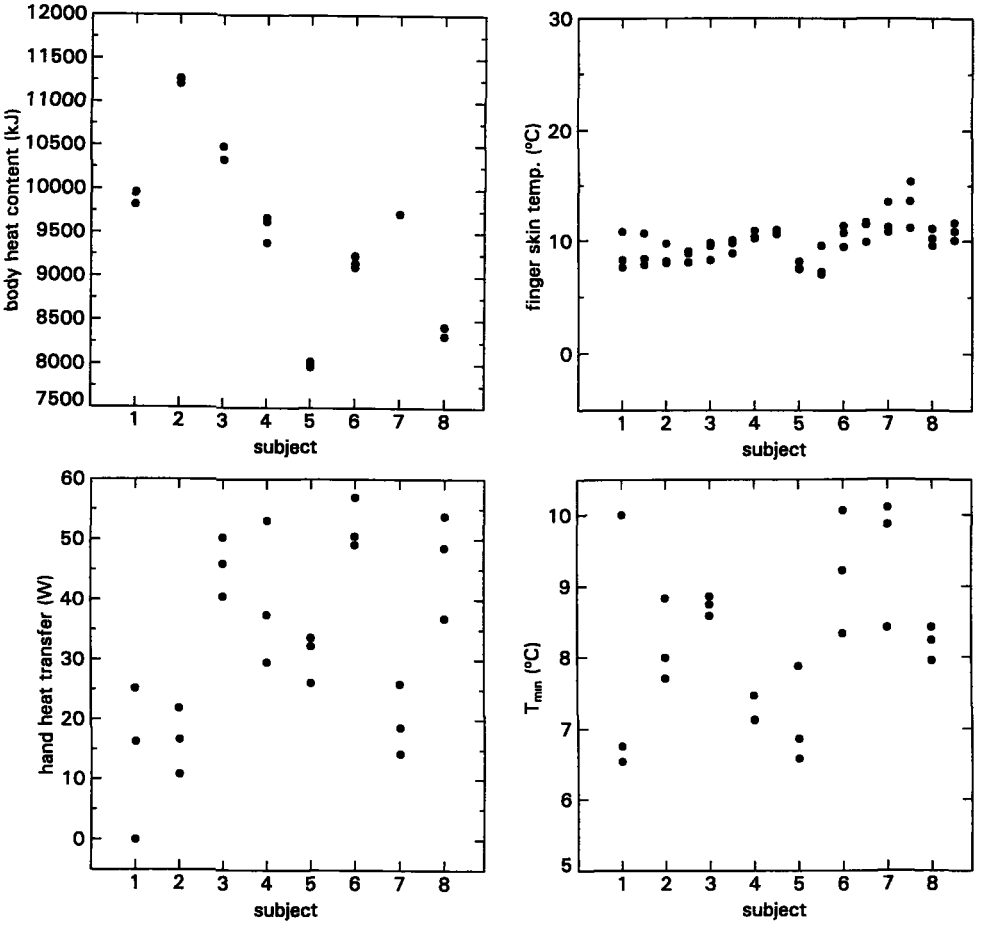

Fig. 11.2 Body heat content (kJ), mean finger skin temperature of the left and right hand (°C), and heat transfer (W) of all trials, averaged over the 10th to 38th minute. Also shown is the T_{min} (°C) for each trial and subject, averaged over all fingers.

There is a large variation in body heat content between subjects, mainly due to the differences in body mass.
The overall results concerning reproducibility are shown in Table 11.2.

The water temperature had a SD of only 0.3°C within subjects (i.e. between the three sessions), and thus was fairly similar. The body heat content also showed a relatively small SD of 48 kJ. Also, T_{re} and $\bar{T}_{sk}$ did not vary much between the three sessions. Therefore it can be concluded that the thermal body conditions for the three trials were relatively similar. The hunting parameters showed more variation: the average SD of T_{min} between sessions was 0.7°C, and even 1.3°C for T_{max}. The SD for the onset time was almost 1 minute. However, for these parameters the variation between subjects exceeded the variation between sessions. The hunting reaction thus is characteristic for every individual.
The pain rating and temperature sensation were fairly consistent within subjects and did not differ between both hands. Only subject 6 showed inconsistencies for unknown reasons.

Table 11.2 Reproducibility of the hunting reaction for the eight subjects. The mean and SD for each subject is based on three trials. CV= Coefficient of Variation. * = only two data points, due to missing data.

Subject→ Variable↓	1		2		3		4	
	mean	SD	mean	SD	mean	SD	mean	SD
T_{re} (°C)	37.4	0.2	37.9	0.1	38.2	0.3	38.0*	0.1
$\bar{T}_{sk}$ (°C)	32.9	0.7	33.9	0.0	33.7	0.5	32.6	0.5
T_w pre-imm. (°C)	5.7	0.2	5.7	0.3	5.8	0.4	5.9	0.3
T_w (°C)	6.1	0.3	6.1	0.4	6.5	0.4	6.3	0.2
body heat (kJ)	9911	79	11240	32	10386	88	9652*	24
$\bar{T}_{fi}$ pre-imm. (°C)	26.6	2.4	29.8	1.4	33.4	0.7	30.7	1.5
$\bar{T}_{fi}$ left (°C)	8.9	1.7	8.7	1.0	9.2	0.8	10.5	0.4
$\bar{T}_{fi}$ right (°C)	9.0	1.5	8.7	0.5	9.6	0.6	10.9	0.2
heat transfer (W)	20.7*	6.2	25.8	4.3	45.6	4.9	40.1	12.0
Doppler flow (a.u.)	1.0	0.3	1.4	0.4	1.2	0.1	2.8	0.9
T_{min} (°C)	7.8	1.9	8.2	0.6	8.7	0.1	7.2	0.2
Δt_{onset} (min)	8.8	3.9	6.3	0.2	7.9	1.0	5.8	0.3
T_{max} (°C)	9.3	1.5	9.6	0.8	11.2	0.3	14.0	1.3
period (min)	9.2	4.1	9.3	0.9	10.3	1.6	8.9	0.8
amplitude (°C)	1.5	0.7	1.5	0.8	2.5	0.2	6.8	1.5
PCC	0.72	0.22	0.24	0.20	0.46	0.05	0.39	0.14
PCC neighbours	0.83	0.12	0.39	0.16	0.60	0.10	0.78	0.08
pain rating	2.9	1.0	6.3	2.1	2.8	0.5	1.5	0.5
temp. rating	-5.4	0.5	-6.7	2.0	-4.1	0.8	-2.6	0.4

Subject→ Variable↓	5		6		7		8	
	mean	SD	mean	SD	mean	SD	mean	SD
T_{re} (°C)	37.9	0.2	37.9	0.3	38.2	0.1	38.1	0.3
$\bar{T}_{sk}$ (°C)	33.9	0.3	33.9	0.3	33.3*	0.1	33.1	0.3
T_w pre-imm. (°C)	5.7	0.3	5.9	0.3	6.3	0.5	5.8	0.1
T_w (°C)	6.0	0.4	6.5	0.3	6.6	0.4	6.4	0.0
body heat (kJ)	7999	30	9166	67	9722*	1	8393	60
$\bar{T}_{fi}$ pre-imm. (°C)	26.2	2.4	31.7	1.5	32.6	0.8	33.0	0.6
$\bar{T}_{fi}$ left (°C)	7.7	0.4	10.5	1.0	11.9	1.5	10.3	0.8
$\bar{T}_{fi}$ right (°C)	8.0	1.4	11.0	1.0	13.4	2.1	10.9	0.8
heat transfer (W)	30.7	4.0	52.2	4.2	19.7	5.9	46.4	8.7

Subject→ Variable⇓	5		6		7		8	
	mean	SD	mean	SD	mean	SD	mean	SD
Doppler flow (a.u.)	1.7	0.3	1.5	0.6	2.3	0.9	2.9	1.4
T_{min} (°C)	7.1	0.7	9.2	0.9	9.5	0.9	8.2	0.2
Δt_{onset} (min)	8.4	0.4	5.8	0.3	5.7	0.7	6.6	0.3
T_{max} (°C)	7.9	0.7	12.6	1.2	15.5	3.5	12.5	1.1
period (min)	7.2	0.9	9.7	1.6	7.0	2.3	9.0	1.6
amplitude (°C)	0.8	0.1	3.4	0.7	6.0	3.5	4.3	0.9
PCC	0.38	0.19	0.54	0.10	0.52	0.24	0.44	0.24
PCC neighbours	0.71	0.18	0.67	0.05	0.63	0.20	0.75	0.09
pain rating	3.0	0.2	3.8	2.4	5.3	0.5	3.2	0.6
temp. rating	-3.1	0.2	-4.4	1.1	-6.0	0.2	-3.4	0.7

Subject→ Variable⇓	Mean	SD within subjects	SD between subjects	CV within subj.
T_{re} (°C)	38.0	0.2	0.2	0.01
$\bar{T}_{sk}$ (°C)	33.4	0.3	0.5	0.01
T_w pre-imm. (°C)	5.9	0.3	0.2	0.05
T_w (°C)	6.3	0.3	0.2	0.05
body heat (kJ)	9559	48	976	0
$\bar{T}_{fi}$ pre-imm. (°C)	30.5	1.4	2.6	0.05
$\bar{T}_{fi}$ left (°C)	9.7	1.0	1.2	0.10
$\bar{T}_{fi}$ right (°C)	10.2	1.0	1.6	0.10
heat transfer (W)	35.2	6.3	11.8	0.18
Doppler flow (a.u.)	1.9	0.6	0.7	0.33
T_{min} (°C)	8.2	0.7	0.8	0.08
Δt_{onset} (min)	6.9	0.9	1.2	0.13
T_{max} (°C)	11.6	1.3	2.4	0.11
period (min)	8.8	1.7	1.1	0.19
amplitude (°C)	3.4	1.0	2.1	0.31
PCC	0.46	0.17	0.13	0.37
PCC neighbours	0.67	0.12	0.13	0.18
pain rating	3.6	1.0	1.4	0.27
temp. rating	-4.5	0.7	1.4	-0.17

comparison between temperature measurement and Doppler flowmetry
A typical time profile of the three sensors is shown in Fig. 11.3.

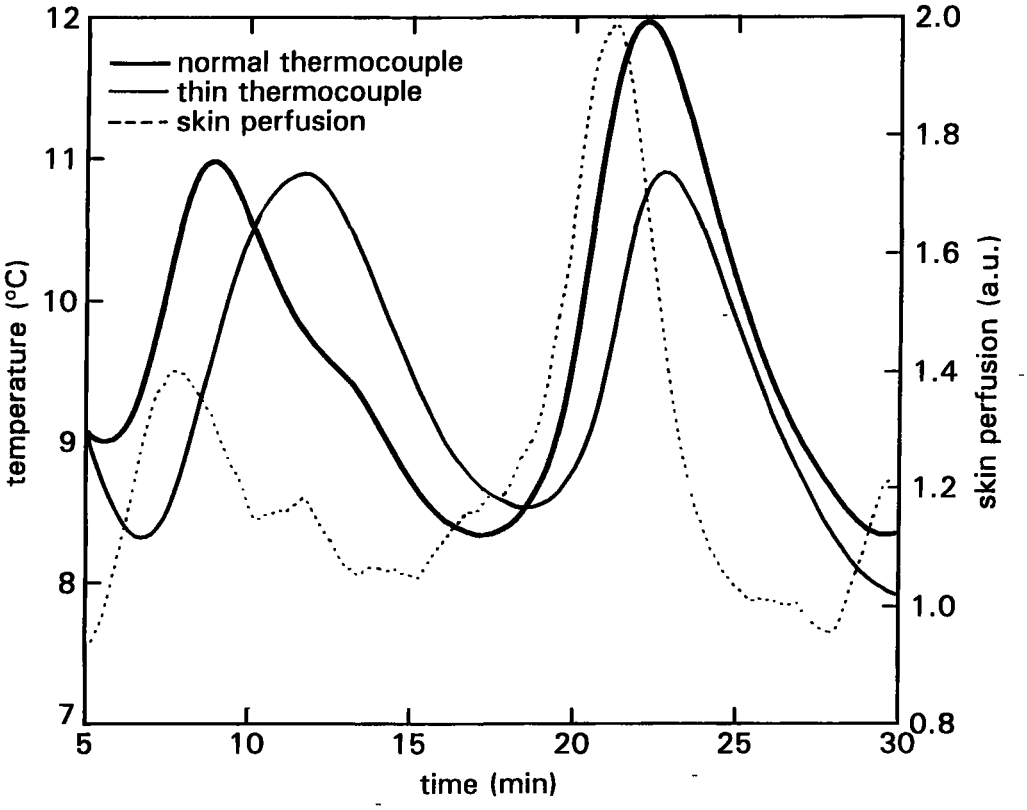

Fig. 11.3 Typical plot of finger skin perfusion (arbitrary units) and finger skin temperature, determined by a normal and thin thermocouple (°C).

The temperature registration of the finger tips and the laser Doppler signal were rather similar but shifted in time. On average, the skin perfusion preceded the temperature response of the normal thermocouple by 112 ± 72 s. The average maximal cross correlation coefficient (MCCC) was 0.76 ± 0.14.

Some subjects had a more pronounced hunting reaction than others. When the hunting reaction had a relatively large amplitude the time delay was shorter. Of all 24 registrations, 12 had an amplitude of over 2.5°C and 12 were below this amplitude. Three responses from the low amplitude group were removed since the skin perfusion and temperature response were unrelated. The high

amplitude group showed a delay of 84 ± 48 s and the low amplitude group showed a delay of 156 ± 84 s.

11.4 Discussion

reproducibility

The relatively high reproducibility of the amplitude parameters of the hunting reaction, as found by Meehan (1955), was not found in this study. Meehan (1955) reported that the average finger temperatures of the subjects were within a range of about 0.5°C. In this study the average finger temperature within subjects during immersion was more variable between experiments (mean SD = 1.0°C). The variation in T_{min} in our investigation (SD = 0.7°C) was also higher than Meehan's results with values within a range of about 1°C (SD ≈ 0.3°C).

The relatively low reproducibility in this study may be partly due to the variation in body heat content. In subjects 1 and 3 the attempt to keep the body heat content stabile was least successful. Consequently, the largest variation in heat transfer and onset time was found in these subjects. Subject 1 had the highest variation in T_{min}, onset time, period and finger temperature before and during immersion. If subject 1 was omitted, the mean SD of the average finger temperature was reduced from 1.2 to 1.0°C, the SD of T_{min} from 0.70 to 0.52°C, the SD of the onset time from 0.88 to 0.45 minutes and the period from 1.71 to 1.37 minutes. In the previous chapter it was shown that even small changes in body heat content affected the hunting parameters. This is confirmed here.

For all hunting parameters, with the exception of the period, the differences between subjects were greater than the differences within subjects (i.e. between sessions). The period is not only dependent on the body thermal status, but strongly influenced by the temperature of the surrounding medium (e.g., Kramer and Schulze, 1948), which was fixed at about 6°C in this study.

Some methodological factors which may have reduced the reproducibility are:

- immersion depth of the hand. This was not easy to control since a foam collar was attached around the wrist and the hand was therefore invisible for the experimenter. Deeper immersion could have increased the heat transfer of the hand to the water.
- changes in body or hand position. Although the subjects were asked to sit as quiet as possible, they sometimes were shifting their posture to sit more comfortably. This may have affected the peripheral blood flow and thus the skin temperature. Doppler blood flow is known to be extremely sensitive to position changes. Moreover, mental activity and deep breaths are also causing strong changes in the Doppler signal.
- previous activity. Although the subjects were asked to sit quietly for almost an hour in a stable thermal environment, it is possible that the effect of previous activity was not completely ruled out. This might have influenced the body heat content prior to immersion and indirectly the hunting parameters.

comparison between temperature measurement and Doppler flowmetry

Sometimes the thin thermocouple responded earlier than the normal thermocouple, sometimes the reaction appeared later (as in Fig. 11.3). These differences may be due to the location of the thermocouple on the finger tip. It is known that differences exist in temperature response between finger tips, but no studies were found that addressed the temperature differences on one finger pad.

The relation between the finger skin perfusion and finger skin temperature was fair with a MCCC of 0.76 ± 0.14. The time shift was dependent on the amplitude of the hunting reaction. When the cold induced vasodilation (CIVD) is weak, it will take a while to warm the tissue in the finger tip and the finger skin temperature will increase more than 150 seconds after the increase in skin perfusion. If, however, a strong CIVD occurred, the tissue is warmed quickly and the time delay is less than 90 seconds.

Pollock et al. (1993) found significant correlation coefficients (0.56 - 0.92) between Doppler blood flow and temperature without taking a time shift into account. It is shown in this study that the time shift is significant and should be included in the analysis.

Nilsson et al. (1986) found an exponential relationship between steady state Doppler blood flow and finger skin temperature. In the present study only the shape of the response is compared for a transient reaction (CIVD). An absolute comparison is difficult in this study because the skin perfusion is expressed in arbitrary units and parameters such as the haematocrit have to be taken into account for correct quantification.

11.5 Summary

Eight subjects immersed their hands three times in 6°C water on different days. Although the experimental conditions of the three immersions were rather similar (SD of water temperature 0.3°C, SD of body heat content within subjects only 48 kJ), the hunting reaction was not very reproducible. The standard deviation of the onset time within subjects was almost a minute and the SD of T_{max} was 1.3°C. Also, the correlation between the finger tips showed large differences between experiments. The poor reproducibility may partly be explained by the findings in previous chapters that even minor differences in core and mean skin temperature may have a large impact on the hunting reaction. Skin perfusion, as measured by laser Doppler flowmetry, precedes the finger skin temperature response by about 90 to 150 seconds during the hunting reaction. The time shift is dependent on the magnitude of the hunting reaction: a strong response leads to rapid tissue heating and relatively short time delays.

Chapter 12*

Central and peripheral vascular control of the hunting reaction in hypothermia, hyperthermia and thermoneutrality

12.1 Introduction

Exposure to severe cold of some protruding body parts, such as fingers, toes and ears triggers a hunting reaction (Lewis, 1930): five to fifteen minutes after the start of the exposure the local skin temperature suddenly rises and keeps fluctuating afterwards. It has been suggested that cold induced vasodilatation (CIVD) is an effective protector of non-freezing cold injuries (e.g., Iida, 1949).

It has been reported that the ambient temperature has a significant effect on the hunting reaction of the fingers: the finger blood flow increases (Bader and Mead, 1949; Edwards and Burton, 1960; Folkow et al., 1963; Spealman, 1945), the finger skin temperature increases ((Blaisdell, 1951; Kramer and Schulze, 1948; Werner, 1977; Yoshimura and Iida, 1950), the heat transfer to the surrounding medium increases (Elsner et al., 1960; Greenfield et al., 1951b) and the onset of the hunting reaction occurs earlier (Adams and Smith, 1962; Tanaka, 1971a; Yoshimura and Iida, 1950) when the ambient temperature is relatively high.
Although the effect of ambient temperature on the hunting reaction well documented, actual body temperatures are seldom recorded. Only two studies (Blaisdell, 1951; Lee et al., 1996) reported core temperatures (T_c) during the experiments. Blaisdell (1951), however, was not able to induce changes in rectal temperature despite exposure to cold. Recently, Lee et al. (1996) measured the CIVD response in an experiment in which T_c was significantly lowered. This study is the only one describing the CIVD response in hypothermic subjects. No study, to our knowledge, has ever investigated the CIVD response during hyperthermia.

The first objective of the present study was therefore to investigate the effects of central and peripheral exposure to cold and heat on the CIVD-responses. For this purpose, eight subjects immersed their right hand in 5°C water and their left hand in 35°C water during hypothermia (C), hyperthermia (W) and thermoneutrality (N).

The mechanism of CIVD is still debated (e.g., Folkow et al., 1963; Shepherd and VanHoutte, 1981). Lewis (1930) concluded from denervation experiments that an axon reflex had to be the primary cause for CIVD. In brief, the axon reflex theory states that peripheral cold pain fibres are triggered by the local cold. The resulting action potential releases vasodilator substances in all collaterals of

*This study is submitted to J. Appl. Physiol.

the neuron. The afferent nerve impulses may inhibit the efferent sympathetic nerve activity. This is possible because the afferent and efferent nerves lie in close vicinity and have minimal insulation. The result is vasodilation in the cold-exposed body parts. Lewis (1930) found that CIVD was still present shortly after sympathectomy, but absent after complete degeneration of the peripheral nerves. Later, however, this complete absence of CIVD response was challenged by others (Table 2.4). Although there are other hypothesized mechanisms to explain CIVD (e.g., Folkow et al., 1963), there is almost no scientific evidence that rejects the axon reflex hypothesis in humans.

It is known that an axon reflex can also be triggered by other stimuli than local cold. The axon reflex caused by electrical stimulation on the skin has been described in detail (Hornyak et al., 1990; Westerman et al., 1987; Magerl et al., 1987). The second goal of this study was to investigate if the electrically evoked axon reflex interferes with the hunting reaction, which is supposed to have the same axon reflex as the underlying mechanism. For this purpose, the experimental setup was expanded with an electrically evoked axon reflex in both middle fingers 15 and 30 minutes after hand immersion. Hornyak et al. (1990) observed that the electrically evoked axon reflex at the dorsum of a hand was inhibited when the subjects were cooled. They suggested that centrally induced vasoconstrictor and locally evoked vasodilator mechanisms compete at the vascular smooth muscle cells. When there is a strong central vasoconstrictor drive, such as during hypothermia, the central sympathetic activity will prevail and the axon reflex will be abolished. When the axon reflex is responsible for CIVD, it is expected that CIVD will almost disappear during hypothermia. The axon reflex and the hunting reaction are expected to reappear when the sympathetic drive is blocked.

Testing the latter hypothesis is the third goal of the present study. In three of the eight subjects the experiment in the hypothermic condition was extended. In these subjects the sympathetic drive was blocked by a local anaesthetic injected in the wrist about 30 minutes after the hand immersion. The axon reflex parameters and hunting parameters were monitored in the remaining immersion period and an enhanced axon reflex and hunting reaction were expected.

12.2 Material and methods

subjects

Eight non-smoking male volunteers with right hand dominance were recruited. Their anthropometric characteristics are shown in Table 12.1. The body fat percentage (BF) was determined by the under water weighing technique and by skinfold measurements on five sites (Plyley et al., 1986).

Table 12.1 Anthropometric data of the subjects. BF = body fat percentage; order shows the sequence in which the conditions C(old), W(arm) and N(eu-tral) were given.

subject	age	stature	weight	left hand volume	right hand volume	esopha-geal inser-tion depth	order of tests	BF skin-fold	BF un-derwater weighing
	(years)	(cm)	(kg)	(cm^3)	(cm^3)	(cm)		(%)	(%)
1	37	188	75	408	424	40.3	CWN	23.0	20.1
2	27	175	66	324	326	39.6	WNC	9.3	10.0
3	39	183	104	519	533	40.6	CNW	22.6	24.5
4	36	185	76	458	460	42.7	NCW	17.5	15.1
5	38	184	98	505	498	41.5	WCN	24.2	24.0
6	24	190	92	404	408	42.7	NWC	18.5	22.1
7	20	178	77	432	460	41.3	CWN	5.4	10.2
8	32	179	74	385	422	40.6	WCN	10.5	13.7
mean	32	183	83	429	441	41.2		16.4	17.5
SD	7	5	13	64	63	1.1		7.1	6.0

All subjects were informed of the details, discomforts and risks associated with the experimental protocol and had been granted medical approval, before they signed a written consent. The protocol was approved by the Human Ethics Committee of the Defence and Civil Institute of Environmental Medicine. Subjects were asked not to use caffeine, alcohol and strenuous physical activity at least 12 hours prior to the test.

methods

In all sessions the temperature of the volar side of the distal phalanx of each finger (T_{fi}) was continuously monitored with fine 40 gauge copper-constantan thermocouples fixed to the skin with surgical tape (3M transpore). An Omega ice point cell (Omega Engineering Inc., USA) was used as the zero reference of the thermocouples. The hands were covered by thin surgical gloves, size L (Oak Technical Inc., Stow OH, USA). The fingers of both hands were immersed to the metacarpophalangeal joints in separate water baths. The left hand was in a 25 l water bath controlled at 35°C by a YSI model 72 proportional temperature controller (YSI, Yellow Springs OH, USA). The bath was continuously stirred by a Haake E52 jet pump (Haake, Berlin, Germany). The right hand was immersed in a 45 l water bath, controlled at 5°C by a Haake F3 temperature controller with integrated jet pump and a Haake EK51-1 cooler.

Red blood cell flow on the skin was determined by laser Doppler flowmetry (Perimed 4000, Järfälle, Sweden) on the volar side of the distal phalanx of the middle fingers and the little fingers of both hands. A 2 mW He-Ne laser was used with a frequency of 15.8 MHz. All measurements were performed within a Doppler frequency range of 20 Hz to 12kHz, an output circuit time constant of 3.0 seconds and a gain of 3. Öberg (1990) showed that a linear relation between blood cell flux and output voltage exists in the selected frequency range. A PF414 angle probe (fibre separation 0.25 mm) was directly taped to the skin, without a probe holder, just beside the stimulation electrode.

A thermistor probe (Baxter Pharmaseal 400 Series Rectal Probe, Valencia CA, USA) continuously measured rectal temperature (T_{re}) 15 cm from the anal sphincter. To determine the esophageal temperature (T_{es}) a thermolinear probe (Mon-a-therm General Purpose, Mallinckrodt Medical, Inc., St. Louis MO, USA) was inserted through the nasal passage. The insertion depth beyond the external nares was based on sitting height, determined prior to the experiments (Mekjavic and Rempel, 1990). The probe was covered with 2% xylocaine gel (Astra Pharma Inc., Mississauga ON, Canada) for lubrification and anaesthesia of the mucosa.
Mean skin temperature of the body ($\bar{T}_{sk}$) was determined by averaging the results of twelve thermistors (YSI, Yellow Springs OH, USA) on the skin, according to the modified Hardy and Dubois weighing coefficients (Hardy and Dubois, 1938; Olensen, 1984).

The axon reflexes were evoked 15 and 30 minutes after hand immersion by electrical stimulation of the ventral part of the distal phalanx of the middle finger with a train of 16 pulses of 1 ms at 2 Hz, according to the optimal settings indicated by Hornyak et al. (1990). A Hewlett Packard 8013B pulse generator triggered pulses of 2 Hz. A relay connected to an Omron H3CA timer transferred the trigger pulses for eight seconds to the external input of a Digitimer DS7 (Digitimer Ltd., Welwyn Garden City, England). This device generated the stimulation pulses with a duration of 1 ms. The current through the finger tip was determined individually in the familiarization run based on the pain-rating and ranged from 15 to 30 mA. The maximum voltage was set at 300 V. This maximum voltage exceeded the maximum of 150 V, as recommended by Westerman et al. (1987). AgAgCl surface electrodes (Sensormedics type 650414, Anaheim CA, USA) with a total diameter of 11 mm and a core diameter of about 2 mm were placed on the ventral part of the distal phalanx of the middle finger. The electrodes were attached to the skin with double sided adhesive electrode rings. A part of the plastic electrode holder and adhesive ring was cut away to enable close placement (about 5 mm core distance) of the Doppler probe. The reference electrode of conducting rubber (30 x 30 x 2 mm) was placed at the dorsal side of the second phalanx of the same finger. The impedance between the stimulation site and the reference electrode was measured prior to stimulation by a Grass model E2M5B 30Hz impedance meter (Grass Inc., Quincy Mass., USA). In order to reduce the impedance, the finger skin was sanded with sand paper at the stimulation and reference site and the dead skin cells were removed with 70% alcohol swabs. Electrode gel (Medical Textiles Manufacturing Inc., Oakville ON, Canada) was put in the stimulation electrode and on the reference electrode.

In Table 12.2 the instrumentation of the fingers of both hands is summarized.

Table 12.2 Instrumentation of the fingers of the left and right hand.

finger	finger skin temperature	finger skin perfusion	electrical stimulation
thumb	x		
index	x		
middle	x	x	x
ring	x		
little	x	x	

Immediately after the stimulation, the pain sensation during stimulation was rated on an 11-point modified Borg scale ranging from "no pain at all" (6), "slightly painful" (8), "rather painful" (10), "painful" (12) and "very painful" (14) to "unbearable pain" (16) (Havenith et al., 1993).

In three volunteers (subject 1, 2 and 4) in condition C the median nerve of the right hand was blocked 30 minutes after hand immersion by injection of 6 to 10 ml 2% lidocaine. In this case, the second axon reflex was evoked 45 minutes after immersion and the hands stayed in the water baths for about 1 hour. Subjects 2 and 4 immersed their nerve-blocked hand in the warm water bath afterwards.

procedure

The subjects underwent three measurement sessions (at least 48 hours apart) in addition to a familiarization run. During the experiments, the subjects were seated on an office chair which was insulated from the ground.

In every session the right hand was immersed in 5°C water and the left hand in 35°C water for 40 minutes. The sessions (thermoneutral, hypothermic and hyperthermic) were given in balanced order (see Table 12.1).

(a) Familiarization run

On the first visit to the lab, the subjects were familiarised with the equipment and the procedures that were used in the measurement sessions. The subjects were dressed in shorts and t-shirt and sat

quietly in a 25°C, 60% relative humidity (RH) climatic chamber for 20 minutes prior to the immersion of the hands.
For the first electrical stimulation the current was set at 15 mA. If the subjects could tolerate higher currents (maximum pain score less than 12), the current was increased by 5 mA until they rated 12 on the pain scale.

(b) Thermoneutral conditions (N)
The subjects were dressed in shorts and t-shirt and sat quietly in a 25°C, 60% RH climatic chamber for 60 minutes prior to the immersion of the hands.

(c) Hypothermic conditions (C)
The subjects, wearing swimming gear, were cooled in a cold water bath for a maximum time of about 3 hours until the esophageal temperature reached 35.5°C. The water temperature upon entry was approximately 18 - 20°C and was lowered to about 12-14°C over the first 90 minutes of immersion. Following the cooling period, the subjects were instrumented with skin temperature sensors and quickly moved within about 8 minutes from the exit of the water bath to a cold (10°C, 60% RH) climatic chamber in order to maintain the level of hypothermia as long as possible. After about 8 minutes in the chamber, during which period the sensors and electrodes were fixed on the subjects hands, the subjects immersed their hands in the water baths.

(d) Hyperthermic conditions (W)
The subjects, wearing shorts only, were warmed in an Exotemp suit, consisting of a hood, vest and trousers (Exotemp, Pembroke ON, Canada). The water in the Exotemp Pro-Kool control bath was set at 48°C and controlled by a YSI model 72 heater. The flow was set at 30 litres per hour. When the esophageal temperature reached 38.0°C the temperature of the circulating water was adjusted such that the esophageal temperature was maintained at 38.0°C. The subjects were sitting in a 30°C, 60% RH climatic chamber. When the 38°C threshold was attained, the hands were immersed in the water.

data analysis
The signals of the thermocouples and thermistors were digitized by a Hewlett Packard 3497A data acquisition control unit, which was connected to a PC by RS-232 ports. The signals were sampled every 10 seconds.

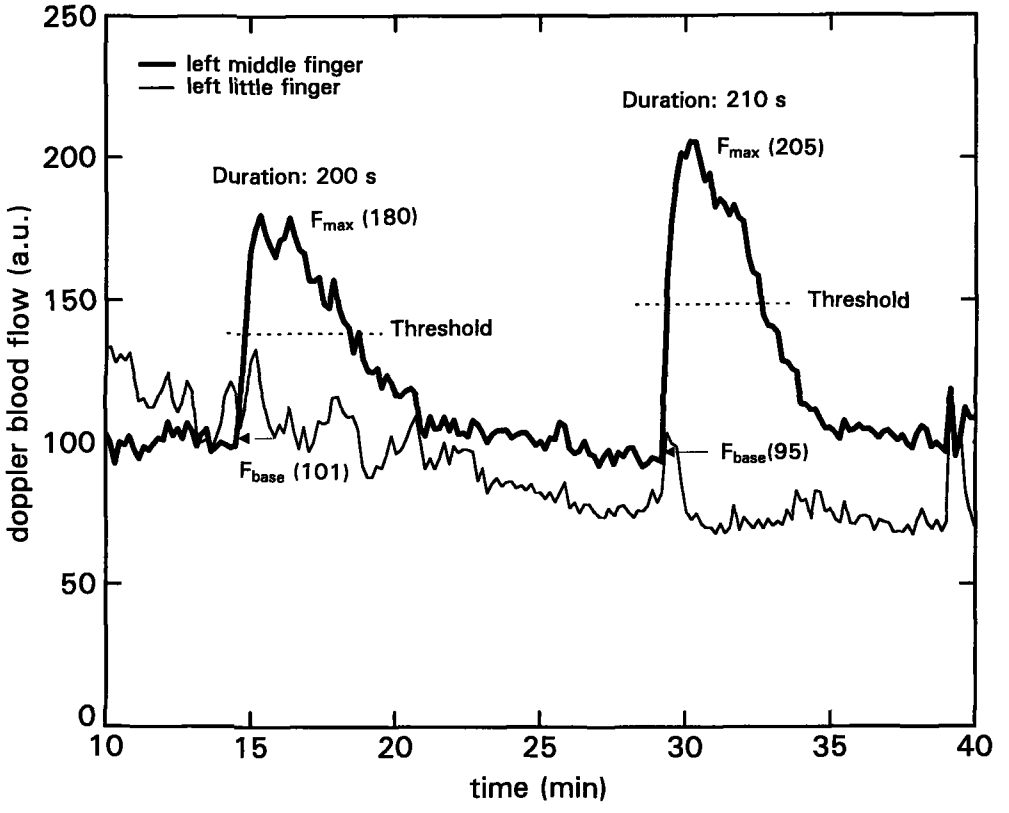

Fig. 12.1 Parameters derived from an actual axon reflex (subject 3, hypothermic condition). The Doppler blood flow of the left middle finger is shown as a solid line; the Doppler blood flow of the little finger is shown as a thin line. Indicated are: the baseline blood flow (F_{base}), the maximal blood flow (F_{max}), the mean blood flow (F_{mean}), the duration of the axon reflex and the calculated threshold.

Several parameters are derived from the Doppler blood flow reaction due to the axon reflex (Fig. 12.1). First, the baseline Doppler flow for a period of 1 minute prior to stimulation (F_{base}) and the maximal flow during a 10 second time frame after stimulation (F_{max}) are calculated. Next, the starting point is determined at which the Doppler signal exceeds a threshold midway between F_{max} and F_{base}. In a similar manner the end of the perfusion increase is determined as the point at which the Doppler signal becomes lower than the threshold. The threshold and duration of the axon reflex are shown in Fig. 12.1 for two axon reflexes. In a pilot study these parameters showed consistent results.

statistics

All results are shown as a mean ± standard deviation (SD). Differences are considered significant if $p<0.05$. The effects of body temperature on the hunting parameters were investigated by a one-way repeated measures Analysis of Variance (ANOVA).

12.3 Results

body temperatures

In Table 12.3 T_{es}, T_{re} and $\bar{T}_{sk}$ are shown for every subject and condition. These temperatures were significantly different between the C, W and N conditions. On average, both estimates of core temperature were outside the normal range for thermoneutrality of 36.8 to 37.7°C (Mackowiak et al., 1992) for the C and W condition.

Table 12.3 Mean esophageal temperature (T_{es}), rectal temperature (T_{re}) and mean skin temperature of the body ($\bar{T}_{sk}$) in °C during 40 minutes of hand immersion, shown for each subject. The SD in the bottom row is the SD between subjects; all other SD's are within subjects.

subject	Hypothermia (C)					
	T_{es}		T_{re}		$\bar{T}_{sk}$	
	mean	SD	mean	SD	mean	SD
1	36.42	0.16	36.60	0.14	22.12	0.26
2	36.48	0.09	36.70	0.09	22.91	0.14
3	36.13	0.11	36.18	0.01	18.35	0.40
4	36.09	0.12	36.61	0.17	23.17	0.16
5	36.82	0.08	37.00	0.02	19.48	0.15
6	36.69	0.11	36.81	0.05	19.35	0.13
7	36.10	0.20	35.43	0.23	22.49	0.16
8	34.37	0.44	35.08	0.12	21.90	0.08
mean	36.14	0.16	36.30	0.11	21.22	0.18
SD	0.76		0.69		1.86	

Table 12.3 continued

subject	Thermoneutral (N)					
	T_{es}		T_{re}		$\bar{T}_{sk}$	
	mean	SD	mean	SD	mean	SD
1	36.82	0.03	37.44	0.02	32.16	0.18
2	36.75	0.09	37.13	0.01	32.21	0.11
3	36.83	0.05	37.36	0.01	31.55	0.03
4	36.99	0.10	37.46	0.04	32.22	0.05
5	36.57	0.09	36.93	0.06	30.94	0.04
6	36.94	0.05	37.30	0.02	30.66	0.03
7	37.07	0.03	37.45	0.01	32.70	0.08
8	36.40	0.14	37.30	0.01	32.23	0.05
mean	36.80	0.07	37.30	0.02	31.83	0.07
SD	0.22		0.19		0.71	

subject	Hyperthermia (W)					
	T_{es}		T_{re}		$\bar{T}_{sk}$	
	mean	SD	mean	SD	mean	SD
1	38.08	0.04	38.34	0.08	37.98	0.09
2	37.86	0.04	38.43	0.17	38.37	0.13
3	38.17	0.08	38.28	0.16	38.09	0.10
4	37.82	0.08	38.27	0.11	38.29	0.19
5	37.83	0.06	38.35	0.08	38.21	0.08
6	38.02	0.05	38.57	0.10	37.95	0.09
7	38.11	0.09	38.66	0.08	37.94	0.15
8	38.12	0.17	38.81	0.10	36.35	0.23
mean	38.00	0.08	38.46	0.11	37.90	0.13
SD	0.14		0.20		0.65	

The cooling duration ranged from 50 minutes to over three hours (average 114 ± 48 minutes). Despite the three hour cooling duration in subject 5, T_c hardly dropped. T_{es} and T_{re} were even slightly higher in the C than in the N condition. Even though, this offers interesting data since it enables the investigation of the effect of $\bar{T}_{sk}$ alone on the hunting parameters, because T_c is not different between condition C and N and $\bar{T}_{sk}$ is much lower in condition C as compared to condition N.
Subject 8 showed a long afterdrop following cooling, which leads to an average T_{es} as low as 34.37°C. In the heat, subject 8 had a very high core temperature and a relatively low $\bar{T}_{sk}$. The extreme results of subjects 5 and 8 are included in the analysis, since they are representative for the wide range of thermal physiological reactions that are often seen during whole body cooling and warming.

The heating periods ranged from 1 hour to 1 hour and 25 minutes, except for subject 6 who was heated for over 3 hours before he reached the 38°C limit (average 84 ± 44 minutes).

In Fig. 12.2 the body core temperatures (T_{re} and T_{es}) are shown as a function of time, and represent the averages for the 8 subjects during the hand immersion for the C, N and W condition. Fig.12.3 shows the mean skin temperature of the body as a function of time.

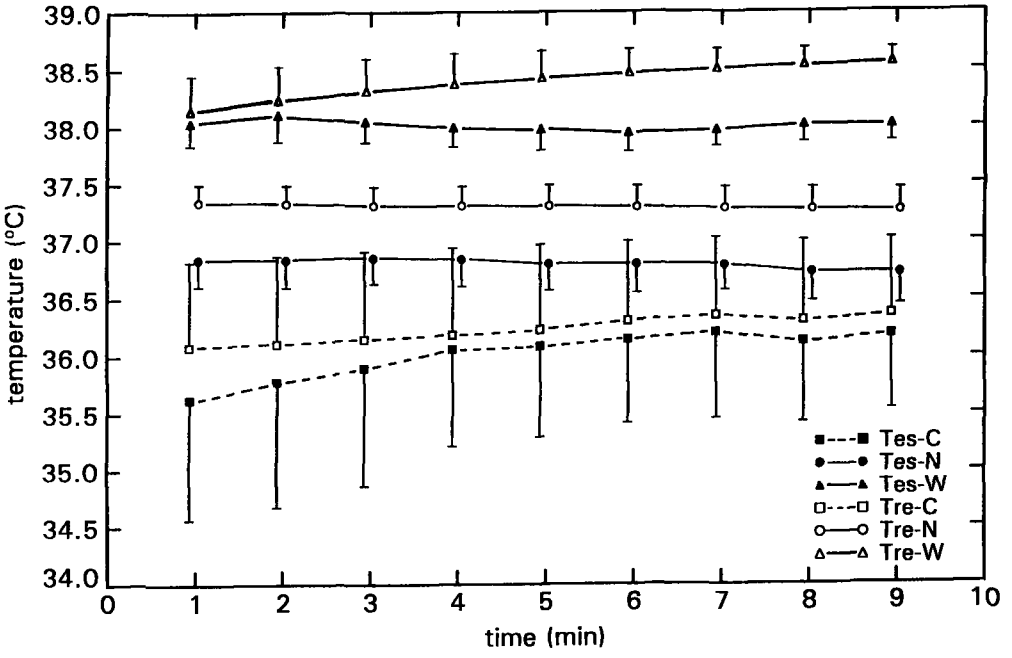

Fig. 12.2 Esophageal (T_{es}) and rectal (T_{re}) temperatures with standard deviation during the hand immersion experiment, averaged over all subjects for 5 minute time intervals. The results are shown for the hypothermic (-c(old)), thermoneutral (-n) and hyperthermic (-w(arm)) conditions.

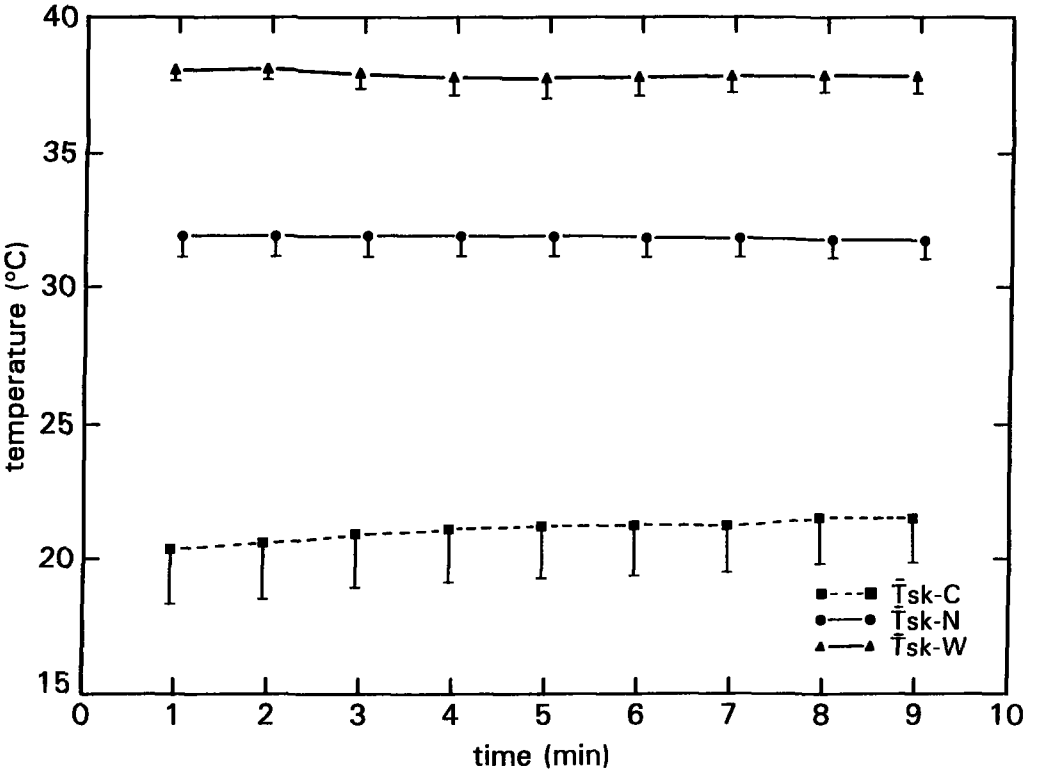

Fig. 12.3 Mean skin temperatures ($\bar{T}_{sk}$) with standard deviation during the hand immersion experiment, averaged over all subjects for 5 minute time intervals. The results are shown for the hypothermic (-c(old)), thermoneutral (-n) and hyperthermic (-w(arm)) conditions.

In the C condition a slow, but insignificant, rise in T_{es}, T_{re} and $\bar{T}_{sk}$ was seen during the hand immersion period (the esophageal temperature raised on average from 35.6 to 36.2°C). This could be explained by the metabolic heat production due to shivering exceeding the heat loss of the naked body in the cold. Despite this raise, the subjects never reached normothermia. In the N condition the body temperatures were very stable. In the W condition T_{re} showed a continuous significant increase from about 38.2 to 38.6°C, while T_{es} and $\bar{T}_{sk}$ stayed fairly constant. T_{re} was consistently higher than T_{es}, by an average of 0.16°C in the C condition, 0.50°C in the N condition and 0.46 in the W condition respectively.

hunting reaction

Table 12.4 shows the hunting parameters as measured in the cold hand for each subject and experimental condition. In condition W, the electrical stimulation caused a decrease in finger skin temperature. This temporary decrease was removed from the analysis. $\bar{T}_{fi}$, $T_{fi,min}$ and $T_{fi,max}$ are higher for the N than for the C condition. In the W condition, the temperature continuously stayed at a high level for all subjects but subject 6 who had a large hunting amplitude. Therefore, the onset and peak times could not be determined in the W condition. In the C condition both the onset time and peak time were significantly prolonged as compared to the N condition.

Table 12.4 Hunting parameters for each subject as measured during the 40 minutes cold exposure of the right hand. $\bar{T}_{fi}$ = mean finger temperature in °C; $T_{fi,min}$ = first minimum finger temperature after immersion in °C; onset time = time from immersion to $T_{fi,min}$ in minutes; $T_{fi,max}$ = first maximal finger temperature after immersion in °C; peak time = time from $T_{fi,min}$ to $T_{fi,max}$ in minutes. Since no hunting reaction was observed in the W condition, onset time and peak time could not be measured. μ = mean. The SD in the last row denotes the SD between subjects; all other SD's are within subjects.

subject	Hypothermia (C)									
	$\bar{T}_{fi}$		$T_{fi,min}$		onset time		$T_{fi,max}$		peak time	
	μ	SD	μ	SD	μ	SD	μ	SD	μ	SD
1	5.9	0.7	5.2	0.1	14.4	6.5	6.6	1.7	29.2	3.0
2	6.5	1.4	5.3	0.0	18.0	3.4	9.8	3.0	32.0	3.7
3	7.8	1.4	5.6	0.4	11.0	2.0	9.6	2.0	24.4	2.0
4	5.4	0.2	5.2	0.1	18.8	5.3	5.6	0.8	27.2	8.0
5	9.3	1.8	5.4	0.2	10.2	1.3	10.9	0.8	19.2	5.3
6	6.8	0.6	5.6	0.1	7.8	0.8	7.9	1.6	13.6	1.1
7	6.0	0.7	5.4	0.1	12.4	0.9	7.7	1.2	20.6	1.7
8	6.8	0.9	5.4	0.1	11.4	1.1	8.5	1.0	23.2	4.2
μ	6.8	0.9	5.4	0.1	13.0	2.7	8.3	1.5	23.7	3.6
SD	1.2		0.2		3.8		1.7		5.9	

subject	Thermoneutral (N)									
	$\bar{T}_{fi}$		$T_{fi,min}$		onset time		$T_{fi,max}$		peak time	
	μ	SD	μ	SD	μ	SD	μ	SD	μ	SD
1	6.3	0.9	6.1	1.1	10.8	11.9	8.8	1.7	15.2	12.2
2	7.2	0.8	6.0	0.4	6.9	1.3	9.3	2.5	12.8	5.9
3	10.5	1.3	9.2	0.8	7.5	1.5	15.2	1.8	12.4	0.2
4	6.9	0.9	5.6	0.2	8.5	1.5	9.6	1.6	13.4	2.7
5	7.5	1.1	6.2	0.8	7.5	0.9	7.1	1.0	13.8	3.6
6	9.7	1.3	7.7	1.6	3.8	0.8	13.8	3.1	6.6	2.0
7	6.8	0.9	5.5	0.5	7.8	0.5	9.0	1.8	11.6	0.6
8	10.0	2.1	8.7	1.1	4.7	1.3	15.2	3.6	8.4	2.4
μ	8.1	1.2	6.9	0.8	7.2	2.5	11.0	2.1	11.8	3.7
SD	1.7		1.4		2.2		3.2		2.9	

subject	Hyperthermia (W)					
	$\bar{T}_{fi}$		$T_{fi,min}$		$T_{fi,max}$	
	μ	SD	μ	SD	μ	SD
1	16.5	1.7	12.0	3.1	20.1	3.4
2	18.5	1.3	15.8	4.0	21.5	3.7
3	15.5	1.0	12.8	1.0	18.5	1.6
4	16.2	0.7	13.5	0.9	19.1	1.6
5	17.4	1.2	12.9	2.0	23.0	3.4
6	11.4	3.6	8.3	0.9	24.7	1.3
7	18.1	1.0	17.9	0.2	20.3	1.6
8	18.5	0.8	17.7	1.3	19.8	1.7
μ	16.5	1.4	13.9	1.7	20.9	2.3
SD	2.3		3.2		2.1	

Fig. 12.4 shows the temporal evolution of mean finger temperatures for both hands during the water immersion period, averaged over all subjects for each condition. In condition W the finger temperatures of the warm hand sometimes exceeded the water bath temperature of 35°C, which indicates that even in that hot water bath some heat loss has occurred, which is consistent with the observations of Ducharme and Tikuisis (1994). The mean temperature of the fingers of the cold hand was relatively high in the W condition and low in the C condition. In condition W the mean finger skin temperature of the cold hand showed an average decrease of about 2 °C after electrical stimulation.

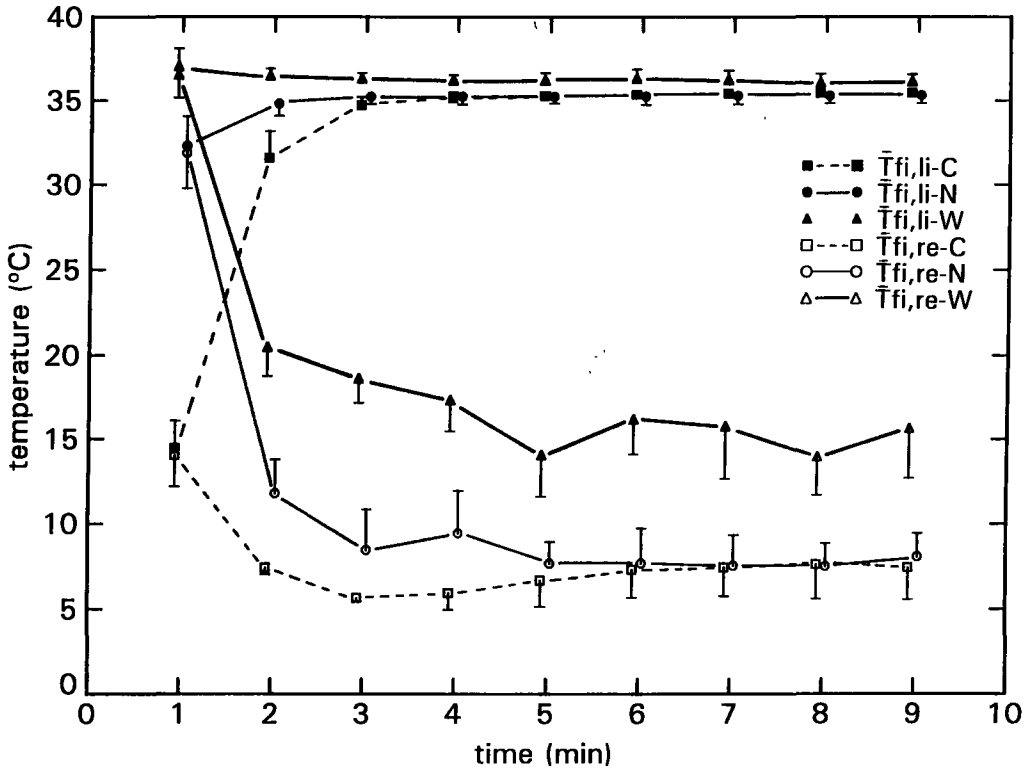

Fig. 12.4 Mean finger skin temperatures ($\bar{T}_{fi}$) for the warm and cold hand with standard deviation during the immersion of the right hand in 5°C water and the left hand in 35°C water. Shown are averages over all subjects for 5 minute time intervals. The results are shown for the hypothermic (-c(old)), thermoneutral (-n) and hyperthermic (-w(arm)) conditions.

electrical stimulation

The only visible change in finger skin temperature due to electrical stimulation was a small decrease in finger skin temperature of all fingers in condition W.

The skin perfusion in the warm and cold hand is shown respectively in Fig. 12.5a and 12.5b for condition C, N and W in a typical subject (number 3). In the warm hand axon reflexes are clearly visible after the electrical stimulation 15 minutes and 30 minutes after immersion. No increase in skin perfusion was seen in the cold hand, but some vasoconstriction was present before the stimulation as an indication of stress anticipation (Fig. 12.5b).

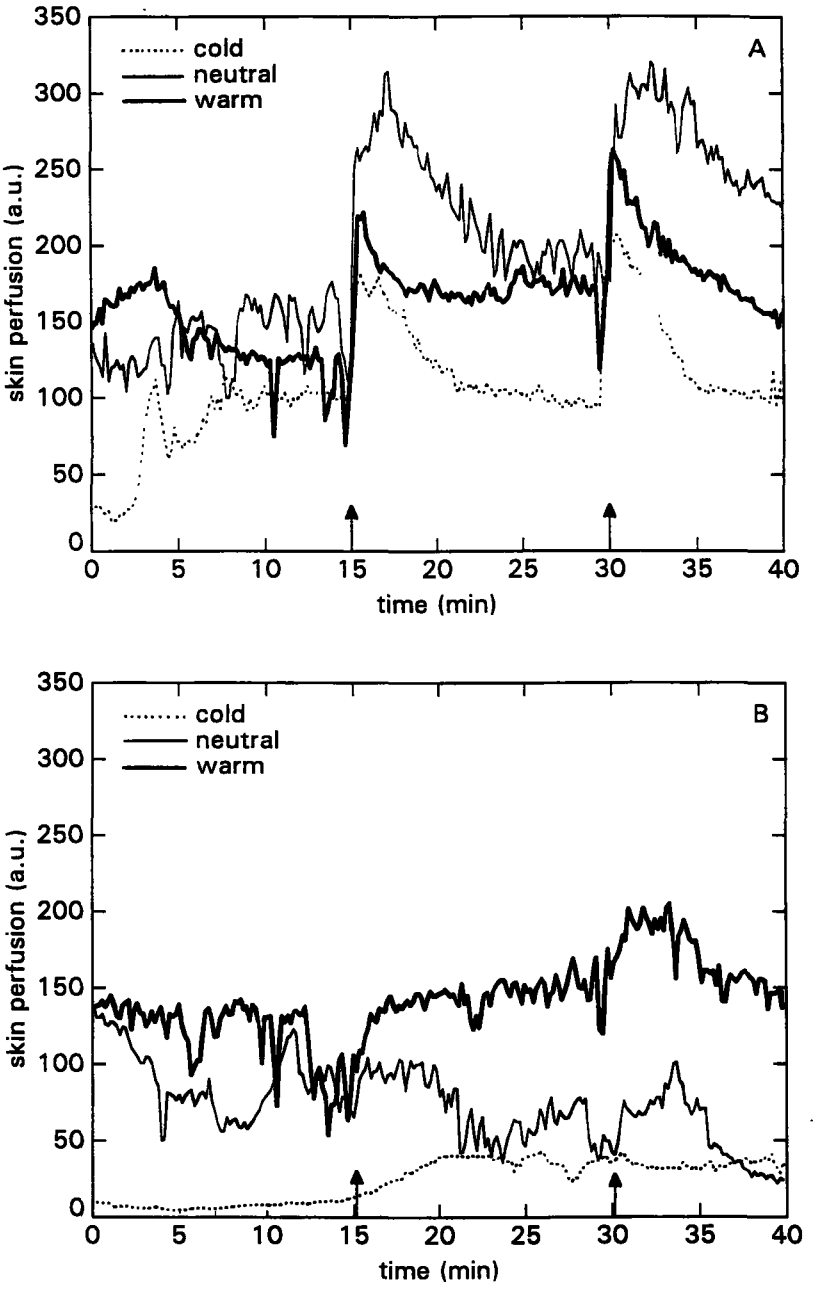

Fig. 12.5 Finger skin blood flow, as measured by laser Doppler flowmetry, for the warmed left (a) and cooled right (b) middle finger during the hand immersion experiment for subject 3. At 15 and 30 minutes electrical stimulation was applied to evoke an axon reflex. The results are shown for the hypothermic (-C(old)), thermoneutral (-N) and hyperthermic (-W(arm)) conditions.

The overall changes in skin perfusion are shown in Table 12.5 for the warm and cold hand before and after the electrical stimulation. Since the results of the first and second stimulation were not different for F_{base} and F_{max} (t-test, $p<0.05$), the mean value of both stimulations is shown. The cold hand had less skin perfusion than the warm hand. The basal finger skin perfusion is related to body temperature: in the warm hand F_{base} was respectively 57 ± 32 for condition C, 136 ± 48 for condition N and 231 ± 75 for condition W. No differences in skin perfusion existed before and after electrical stimulation in the cold hand. In the warm hand, the perfusion generally increased, but the variation in the perfusion response between subjects was large. The maximal skin perfusion due to the axon reflex (F_{max}) was not different between conditions N and W, but was lower for condition C. The mean duration of the axon reflex was shortest during condition C (68 ± 79 s), followed by conditions N (154 ± 95 s) and W (199 ± 152 s). The incomplete data on reflex duration, however, do not enable a sound statistical comparison. As can be expected, the blood flow in the little finger was not affected by the electrical stimulation in the middle finger.

Table 12.5 Doppler blood flow in arbitrary units in the middle finger tip of the warm and cold hand measured before and after the electrical stimulation given 15 and 30 minutes after hand immersion. The average results of the two stimulations are shown. F_{base} is the basal blood flow 1 minute prior to electrical stimulation. F_{max} is the maximal blood flow during 10 seconds after the electrical stimulation. The duration of the reflex (in seconds) is calculated as the time the blood flow exceeds the threshold midway between F_{base} and F_{max}. A bar denotes absence of an axon reflex. The SD in the last row denotes the SD between subjects.

subject	Hypothermia (C)				
	F_{base}		F_{max}		duration
	warm hand	cold hand	warm hand	cold hand	warm hand
1	41	6	147	6	35
2	43	7	56	8	-
3	98	23	193	27	205
4	23	8	24	8	-
5	105	21	127	27	-
6	80	54	205	49	10
7	44	5	52	4	60
8	25	24	69	17	30
mean	57	19	109	18	68
SD	32	16	69	15	79

Table 12.5 continued

subject	Thermoneutral (N)				
	F_{base}		F_{max}		duration
	warm hand	cold hand	warm hand	cold hand	warm hand
1	63	10	245	8	150
2	114	44	261	38	115
3	176	80	316	80	335
4	120	59	185	57	105
5	181	160	294	143	105
6	196	39	447	45	215
7	85	41	257	57	50
8	155	42	204	14	-
mean	136	59	276	55	154
SD	48	45	81	43	95

subject	Hyperthermia (W)				
	F_{base}		F_{max}		duration
	warm hand	cold hand	warm hand	cold hand	warm hand
1	190	27	240	11	65
2	333	127	395	153	95
3	91	123	241	155	395
4	210	117	278	111	240
5	225	178	221	186	-
6	225	-	234	-	-
7	310	152	326	106	-
8	265	191	272	130	-
mean	231	131	276	122	199
SD	75	54	59	56	152

In Table 12.6 the impedance and pain score is shown for each experimental condition for both hands. The impedances of the little finger and middle finger were not different (t-test, $p<0.05$), and were averaged in the table. The impedance was highest for the cold hand and higher when the body core was colder (higher for condition C than for N and higher for condition N than W). Pain was more pronounced in the warm hand. For this hand the pain was most pronounced in condition N as compared to C and W. The pain in the cold hand was not dependent on experimental conditions.

Table 12.6 Impedance measured prior to stimulation (in kΩ) and pain score following stimulation for the warm and cold hand during hypothermia, normothermia and hyperthermia. All results are shown ± SD and averaged over all subjects.

	Hypothermia (C)		Thermoneutral (N)		Hyperthermia (W)	
	warm hand	cold hand	warm hand	cold hand	warm hand	cold hand
Impedance (kΩ)	111 ± 14	172 ± 7	100 ± 17	131 ± 17	32 ± 7	41 ± 12
Pain	12.1 ± 0.6	10.1 ± 1.2	13.4 ± 0.6	10.7 ± 0.4	11.3 ± 0.2	11.0 ± 0.7

median nerve block

The effect of the median nerve block is shown in Fig. 12.6 for the three volunteering subjects (1, 2 and 4) in condition C.

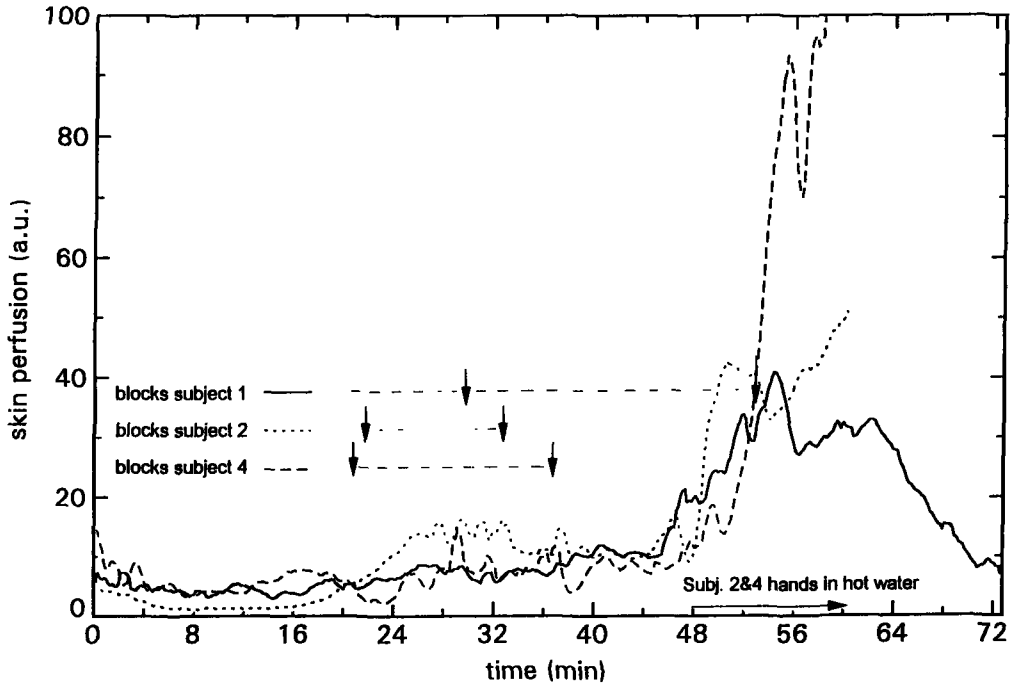

Fig. 12.6 Skin perfusion (perfusion units - a.u.) of the middle finger of the cold hand in three hypothermic subjects during immersion in 5°C water. The arrows indicate the moment of injection of ml 2% lidocaine in the wrist, close to the median nerve. Subjects 2 and 4 immersed their hands in a 35°C water bath afterwards

The injection time of local anaesthetics is marked in Fig. 12.6. The anaesthetic agent generally becomes effective 5-10 minutes after injection. The effectiveness of the block was confirmed by the absence of any sensation when the middle finger was stimulated (300 V, 15-30 mA). The finger skin temperatures and skin perfusion were not affected by the nerve block. The perfusion increase in the middle finger of subject 2 was initiated prior to the injection, and can thus be seen as a normal hunting reaction. This is also illustrated by the fact that the skin perfusion returned to baseline values in subject 1 after about 1 hour of immersion.

To confirm the effectiveness of the block, subjects 2 and 4 reimmersed their cold hand in the warm water bath after the experiment. At this point in time, the local cold stress is removed and if the block is effective, there should be no centrally induced vasoconstrictive activity. A strong increase in skin perfusion was seen for the middle and little finger. The perfusion increase in the middle finger exceeded the increase in the little finger.

12.4 Discussion

the effect of body temperatures on the hunting reaction

This study clearly shows that the hunting reaction is more pronounced when the body core is warm and that hunting is minimal, but not abolished, when the body core is cold. There is some evidence in the literature that indicates that T_c and $\bar{T}_{sk}$ have different effects on the hunting parameters. Blaisdell (1951) cooled subjects, which resulted in a decreased $\bar{T}_{sk}$, but not T_c. He found a decrease in $T_{fi,min}$ but no changes in frequency and amplitude of the hunting reaction. Lee et al. (1996) decreased both T_c and $\bar{T}_{sk}$. They found a relation between T_c and $\bar{T}_{fi}$. Daanen et al. (1997) found that $\bar{T}_{fi}$ was dependent on T_c and onset time was determined mainly by $\bar{T}_{sk}$. In the present study, cooling and heating of the subjects lead to a simultaneous change in T_c and $\bar{T}_{sk}$. $\bar{T}_{fi}$ was higher for condition N than for condition C and higher for condition W than for N. The onset time was longer for condition C than for condition N. In subject 5, however, $\bar{T}_{sk}$ decreased in condition C as compared to condition N by 11.5°C, while T_c was slightly higher in condition C (T_{es}: 36.82°C) than in condition N (T_{es}: 36.57°C). For this subject, $\bar{T}_{fi}$ was also higher in condition C (9.3°C) than in N (7.5°C), which is consistent with the previous findings. Comparable to the other subjects, the onset time was longer in condition C than in condition N, which shows that $\bar{T}_{sk}$ has a potent influence on onset time. These results support the conclusions of Daanen et al. (1997) observed for milder hypothermic conditions (a decrease of 0.3°C in rectal temperature as compared to 1°C in the present study and $\bar{T}_{sk}$ values of about 23°C as compared to 21°C in the present study).

Werner (1977) showed that the amplitude of the hunting reaction was maximal at thermoneutrality. In our experiments the hunting amplitude was not significantly different between the conditions ($F(2,14)=3.66$; $p>0.05$), but there was a trend that the amplitude increased with body temperature.

finger blood flow

In condition W the blood flow in the fingers was continuously elevated transferring the excess body heat to the cold water through the fingers. In some subjects, heat was even lost from the warm hand since the finger temperatures exceeded the water temperature.

In condition C the blood flow in the fingers was very low, since heat was preserved in the body. However, even in condition C, CIVD occurred in due time in all subjects (average 13 minutes, Table 12.4).

effect of electrical stimulation in the cold hand

In the cold hand no increase in skin perfusion was noted after electrical stimulation. It is possible that the vasoconstriction induced by the local cold stimulus caused a very high tissue impedance (Keatinge, 1970). This may have resulted in a current through the finger tip below the threshold to evoke an axon reflex. This explanation is supported by the finding that the impedance is generally higher in the cold hand as compared to the warm hand and that the pain is slightly less (Table 12.6). No perfusion increase was found, however, in those cases where the skin impedance was low, for instance in the W condition.

It is possible that the stimulation of pain fibres triggered the axon reflex in the cold hand, but that this did not lead to vasodilation and increased perfusion. Either the vasoactive substances may not be released or their release may have no effect. It has been reported that the tissue and blood temperature are low in cold hands. Edwards and Burton (1960) calculated that the arterial blood temperatures could even be lower than 8°C. The low blood and surrounding tissue temperature lead to vascular contraction, regardless of nervous activity (Keatinge, 1970; Keatinge and Harman, 1980). The absence of changes in skin perfusion in the cold hand, despite similar stimulation as in the right hand, shows that local skin temperature is relatively more important in respect to axon reflexes than the thermal status of the body.
A reduction in finger skin temperature of all fingers was seen in the cold hand after stimulation in the W condition. The likely explanation is that the pain caused an increase in sympathetic activity, resulting in a temporary peripheral vasoconstriction (Ochoa et al., 1993). This vasoconstriction was only detectable in the W condition with its low basal sympathetic activity.

effect of electrical stimulation in the warm hand
The increase in skin perfusion in the warm hand was most pronounced in conditions N and W (Table 12.5). In condition C, peripheral vasoconstriction probably increased the impedance (Table 12.6). This in turn decreased the current and thus it is likely that the pain fibres received a reduced stimulus. The pain response was reduced in the C condition as compared to the N condition (Table 12.6). In the W condition, sweat accumulated in the glove of some subjects. This caused very low impedances, so that the current may have gone through the sweat, rather than through the skin. This is reflected by a reduced pain response (Table 12.6) as compared to the N condition.
Hornyak et al. (1990) concluded from their data that increased sympathetic activity caused by a decreased body core temperature inhibited the axon reflex. In the present investigation an inhibition of the axon reflex was observed for condition C as compared to conditions N and W in the warm hand. This tends to support the observations of Hornyak et al. (1990). We could not verify the hypothesis for the cold hand in the present study, because no changes in skin perfusion were found after electrical stimulation. In the study of Hornyak et al. (1990), the skin impedance was not measured and it is possible that an increase in skin impedance reduced the stimulus to the pain fibres and also the subsequent response. Ideally, the current, voltage and/or impedance should have been measured simultaneously during the stimulation.

median nerve block
Fig. 12.6 shows that the nerve block had no visible effect on the hunting reaction. In our study, a large amount of 2% lidocaine was injected two times and the effectiveness of the block was verified by electrical stimulation. It could safely be assumed that the sympathetic vasoconstrictor activity was abolished ten minutes after the second injection. Previous experiments showed that the peripheral blood flow increased after nervous blockade (Table 2.3), but there are some differences between the reported studies and the present study.

The first difference is the hypothermic condition of the subjects. Saumet et al. (1992) investigated the effect of a nervous block (10 ml 1% lidocaine infiltration in the wrist) in thermoneutral, cooled and warmed subjects. The cooling, however, was minimal, resulting in a $\bar{T}_{sk}$ of 30.1 and a T_{re} of 37.7 °C. Similar to the other studies in Table 2.3, the blood flow was higher in the blocked hand than in the control hand during cooling in Saumet's study. During heating of the body ($\bar{T}_{sk}$ of 39.3°C) blood flow was very high in both the blocked and control fingers.
The second difference is the temperature of the surrounding medium of the hands. In the studies of Freeman (1935), Thomsen et al. (1988), and Warren et al. (1942) the temperature of the medium surrounding the hands was rather high and this explains the increase in blood flow, similar to the increased blood flow in the hands of subjects 2 and 4 after reimmersion in 35°C water (Fig. 12.6).
A third difference is that not the same part of the hand is immersed. In the studies of Greenfield et al. (1951b), Lewis (1930) and Gemne et al. (1986) only one finger was in the cold water after the immersion. It is possible that all other fingers showed an increased blood flow after the sympathetic block and that this increased blood flow of the neighbouring fingers affected the blood flow of the immersed finger. In our study all fingers were immersed in the cold water.

In two subjects 2% lidocaine was also injected in condition W. However, the elevated hand blood flow level washed away the blocking agent which was immediately spread through the body and caused nausea in both subjects. These experiments, therefore, were prematurely ended and not included in this study.

is the axon reflex responsible for the hunting reaction?
In the cold hand a normal CIVD pattern was found, which was, as expected, dependent on the thermal status of the body. In that same hand no increase in skin perfusion was found after electrical stimulation. If an axon reflex is the origin of CIVD, as hypothesized, it is remarkable that electrical stimulation to trigger the axon reflex did not cause an increase in skin perfusion. The afferent impulses from the cold fibres in the skin, which are supposed to trigger the axon reflex, may be more influential and massive than the afferent impulses from the local electrical stimulation. Increasing the electrical stimulation parameters, however, is unethical, since on average, the subjects already qualified the pain as 'painful' after stimulation. Moreover, the parameters were strong enough to cause unambiguous axon reflexes in the warm hand. It is possible that the action potentials were evoked at the nerve endings, but that the vasoactive substances were either not released or that they were released, but unable to cause vasodilation in the cold blood vessels. The results from the nervous blockade also show that a sudden absence of sympathetic activity hardly affects skin perfusion. CIVD still occurred, despite nervous blockade. There are two possible explanations for this: either the adrenergic neurotransmission is interrupted in the cold (Johnson et al., 1986) and/or the contractile apparatus of the blood vessel wall fails to operate in the cold (Keatinge and Harman, 1980). Therefore, our results are contradictory to the hypothesis that an axon reflex is the origin of CIVD, although there is not sufficient evidence at the moment to reject the hypothesis completely.

Some differences exist in axon reflexes evoked by electrical stimulation and by cold stimulation. Electrically evoked axon reflexes were associated with a sharp pain, which is different from the 'numb' pain which is experienced during local cold exposure of the fingers. Electrical stimulation in the cold hand caused a strong generalized vasoconstriction of short duration in condition W. The blood flow was slightly reduced for less than a minute but the temperature of the finger tips could be decreased for several minutes by several degrees. Immediately after cold water immersion of the hands, the generalized vasoconstriction is only visible in the first few minutes following immersion.

12.5 Summary

To investigate the influence of body thermal status on the Cold Induced Vasodilation (CIVD) response, eight subjects immersed their right hand in 5°C water (and left hand in 35°C water) during hypothermia, thermoneutrality and hyperthermia. High body core and mean skin temperatures appeared to be related to high finger skin temperatures during cold water immersion and shorter onset times to CIVD. To investigate the plausibility of the axon reflex as an explanation for the occurrence of CIVD, axon reflexes were evoked by electrical stimulation during hand immersion. An increase in skin perfusion was seen in the warm hand but absent in the cold hand, which indicates that the axon reflex is not a likely explanation for CIVD. In three subjects the median nerve was completely blocked during hypothermia to investigate the interaction between sympathetic activity and CIVD. The hunting pattern remained unchanged. This indicates that changes in sympathetic activity are not very important for the occurrence of CIVD.

Chapter 13

General discussion

13.1 Hunting as a protective mechanism against cold injuries

In chapters 9, 10 and 12 it was clearly shown that the hunting reaction is most pronounced when the body core is warm and almost absent when the body core is cold. Therefore, one can question the effectiveness of the hunting reaction as a protection against local cold injuries as suggested by Iida (1949). CIVD is almost absent in most situations when it is needed most i.e. when the body core temperature has dropped due to cold exposure (see also Veghte, 1962). In practice, this means that the body core has to be kept warm, for example by exercise, in order to enable the hunting reaction to appear. During prolonged severe cold exposure, as is often the case in military settings or in mountaineering, the thermal balance is hard to achieve. When hypothermia occurs, the cold induced vasodilation (CIVD) reaction has less power and may be unable to prevent the onset of cold injuries in hands and feet. One can argue that this mechanism is optimally tuned to prolong human survival in the cold, but it may be at the expense of loosing an extremity.
Only when the body core is warm and the periphery is cold, the hunting reaction may prevent a body part from cold injury. In chapter 12 it is shown that hyperthermic subjects continually have a very high blood flow in the fingers and will probably not be at risk. However, during severe cooling, the CIVD response appears too late and freezing of the skin may already occur within a few minutes (Keatinge and Cannon, 1960; Wilson and Goldman, 1970). Keatinge (1970) concludes that there are more disadvantages than advantages of the CIVD response: the increased heat loss leads to faster cooling rates of the body core temperature in the cold and results in hypothermia. Therefore, he even advocates the use of vasoconstrictor drugs to suppress CIVD during cold exposure.
In summary, the description of the hunting reaction as an effective mechanism to prevent cold injuries needs to be adjusted: sometimes it appears too late and it is almost absent in hypothermic situations when it is needed most. Moreover, the hunting reaction appears when there is no risk for cold injuries at all. In Chapter 4 of this thesis for example, when the hands were immersed in water of 25°C the same hunting reaction appeared as observed in cold water. In the literature there are no descriptions of cold injuries occurring at these temperatures.

13.2 Correlation studies

number of fingers in between
Many authors observed synchronous hunting reactions between different cooled fingers or between cooled and non-cooled fingers (Table 2.5). However, no quantitative comparison was made

concerning the synchronization. In the present study the amount of synchronization was quantified by the Pearson Correlation Coefficient (PCC). In Table 13.1 the results of the previous chapters are summarized.

Table 13.1 Summary of the Pearson Correlation Coefficient (PCC) values found in this study. n denotes for each chapter how often a hand was immersed (i.e. the number of subjects x the number of investigated hands x the number of sessions per subject). In all chapters but chapter 6, a comparison was made between the PCC's of the two hands. In the column 'other hand' the mean PCC of every possible combination of fingers between the two hands (n x 12½ values) is shown. The PCC values within a hand are shown for 0 (neighbouring fingers), 1, 2 and 3 (thumb and little finger) fingers in between. The number of averaged PCC's is respectively 4 x n, 3 x n, 2 x n, and 1 x n.

chapter	n	other hand		fingers in between							
				0		1		2		3	
		mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
6	12			0.67	0.33	0.55	0.38	0.43	0.47	0.36	0.49
7	32	0.40	0.47	0.67	0.39	0.61	0.40	0.58	0.39	0.57	0.39
8	14	0.19	0.43	0.80	0.25	0.77	0.27	0.76	0.25	0.75	0.30
9	64	0.40	0.44	0.68	0.36	0.60	0.40	0.52	0.44	0.51	0.43
11	48	0.34	0.41	0.67	0.35	0.59	0.35	0.57	0.36	0.54	0.37
mean (weighed)		0.34	0.41	0.68	0.35	0.61	0.37	0.56	0.39	0.54	0.40
SD between experiments		0.09		0.05		0.08		0.11		0.12	

Table 13.1 clearly shows that the PCC between different hands (column 'other hand') is less than the PCC within a hand. The correlation between the fingers of an immersed and a non-immersed hand is rather low (0.19 - Chapt. 8). The correlation between the fingers of two immersed hands is still low (0.34 to 0.40). It does not make a difference for the PCC values if the fingers are immersed simultaneously or with a few minutes interval (Chapt. 7). From these data it can be concluded that, generally, the hunting reactions in the fingers of two contralateral hands are not similar. However, it has to be noted that there are large inter- and intra-individual differences. The relative independence of hunting between the two hands makes it attractive to assume two different vasomotor control centres in the central nervous system: one for the left hand side and one for the right hand side.

Within an immersed hand, the neighbouring fingers show more correspondence in hunting than non-neighbouring fingers, as is evident from Table 13.1. This effect may be due to common neural

control i.e. that the vasomotor control of the peripheral blood vessels is spatially organized, specific at the finger level. In the next paragraph the possibility of common neural control is explored.

innervation

The volar side of the distal phalanx of the fingers is innervated by the ulnar (little finger and ring finger) and the median nerve (ring finger, index finger and thumb).

The data presented in chapter 6 indicates that fingers sharing the same innervation have more correspondence in hunting reaction (i.e. ulnar nerve for the little finger and part of the ring finger and median nerve for the index and middle finger, as compared to the thumb - index finger and middle finger - ring finger). Hence, it is proposed that a nervous component plays a role in CIVD. In Table 13.2 the results concerning innervation are summarized for all chapters.

Table 13.2 Amount of correspondence between the hunting reactions of neighbouring fingers of cold water immersed hands, as quantified by the Pearson Correlation Coefficient.

chapter	n	finger combination							
		little-ring		ring-middle		middle-index		index-thumb	
		mean	SD	mean	SD	mean	SD	mean	SD
6	12	0.76	0.21	0.68	0.40	0.83	0.09	0.42	0.40
7	32	0.59	0.40	0.85	0.23	0.57	0.47	0.66	0.35
8	14	0.88	0.16	0.78	0.29	0.78	0.25	0.75	0.27
9	64	0.73	0.33	0.62	0.38	0.73	0.30	0.62	0.42
11	48	0.74	0.26	0.72	0.32	0.72	0.33	0.50	0.43
mean (weighed)		0.72	0.30	0.71	0.33	0.71	0.32	0.59	0.40
SD between experiments		0.09		0.08		0.09		0.12	

These data show that the correspondence in hunting is not different between the little finger - ring finger, ring finger - middle finger and middle finger - index finger. Only the PCC between the index finger and thumb is less than for the other combinations. If innervation plays a major role, it can be expected that at least the correlation between index finger and middle finger will be higher than for the other combinations. This is not the case, and it can be concluded that specific innervation of the volar side of the distal phalanx of the finger does not play a major role in the hunting reaction.

common vascular control

When the blood flow is increased in one finger, the neighbouring fingers have a higher chance to be warmed up than fingers that are further interspaced. Common neural control is not a plausible explanation, since similarity in nervous innervation (see above) is not related to similarity in hunting patterns. Another explanation may be that the vasodilation in the warmed finger leads to a higher

blood flow and warming up of the surrounding tissue. The warm tissue causes more vasodilation, to begin in the neighbouring finger. The cover of this thesis shows thermograms of CIVD in which one finger after another is warmed. This chain reaction may explain why the other fingers of a hand warm up after one finger has started.

13.3 What causes cold induced vasodilation?

Many hypotheses of the mechanism of CIVD have been proposed since its first description in 1930 (see par. 2.3). Lewis (1930) concluded from denervation experiments that an axon reflex had to be the primary cause for CIVD. This mechanism explains the presence of CIVD after sympathectomy and the absence of CIVD after nerve degeneration. Recently, a renewed interest in the axon reflex has been shown, probably because laser Doppler flowmetry enables measurement of the resulting vasodilation. The axon reflex can be invoked by cold (Lewis, 1930), electrical stimulation on the skin (Hornyak et al., 1990; Westerman et al., 1987; Magerl et al., 1987), intra neural stimulation (Ochoa et al., 1993), electrophoresis of acetylcholine (Walmsley and Wiles, 1990), injection of histamine (Hovell et al., 1987; Izumi and Karita, 1991), injection of substance P (Izumi and Karita, 1991) or injection of nicotine (Izumi and Karita, 1992).
In chapter 12 electrical stimulation was used to evoke axon reflexes in a cold hand during the hunting reaction. Despite strong and painful stimulation of the skin, which resulted in clear axon reflexes in a warm hand, no perfusion increase was found in the cold water immersed hand. If the electrical stimulation can not evoke an axon reflex, are the afferent impulses from the pain cold nerve fibres strong enough to do so? Unfortunately, this question can not be answered at this moment, but some doubt has been raised by the present study on the validity of the axon reflex hypothesis for the explanation of CIVD.
If the axon reflex is ruled out as a likely explanation for CIVD, two main hypothesis on the origin of CIVD remain: paralysis of the contractile apparatus (Keatinge and Harman, 1980) and interruption of the adrenergic neurotransmission in the cold (Johnson et al., 1986). The experimental support for the hypotheses is conflicting. Experiments in animals (Folkow et al., 1963; Gardner and Webb, 1986) showed that NA infusion abolished CIVD, thus stressing the necessity of adrenergic neurotransmission. After iontophoreses of NA through the skin of humans, however, CIVD was still found (Keatinge, 1961), favouring the hypothesis on paralysis of the contractile apparatus. More research is needed to elucidate this controversy.

13.4 Interaction between central and local vasomotor control

It is shown in most chapters of this thesis that body core and mean body skin temperature have a tremendous effect on the magnitude and timing of CIVD. Even small changes in core temperature lead to large changes in the hunting reaction. In hyperthermia the subject can remove large amounts of heat through the cold hands; the finger temperatures continuously stay at a high level. In

normothermia the hunting magnitude is relatively high. In hypothermia the finger skin temperatures stay close to the water bath temperatures with occasional hunting waves.
In the experiments in chapter 10 and 12 it was shown that core temperature was related to the magnitude of CIVD and that the water temperature and mean skin temperature were related to timing aspects (see also par. 13.5). The water temperature and mean skin temperature are important determinants of the tissue temperature in the cold exposed extremity. A low tissue temperature leads to the initiation of CIVD (par. 13.3). Once the vessels are opened up, the core temperature determines the magnitude of the response. The main mediator between core temperature and peripheral blood flow is the sympathetic nervous system. The experiments in chapter 6, 7 and 8 show that it is likely that each extremity is under separate vascular control. It was clearly shown in chapter 12 that peripheral nerve blockade does not abolish the hunting reaction. Therefore, the involvement of such parameters as blood temperature are probably also of importance.
The arteriovenous anastomoses (AVA's) are the most important blood vessels for the hunting reaction. Their relatively large diameter enables large amounts of blood to pass and convey heat to the surrounding tissue. Unfortunately, information of the amount of AVA's is lacking and research should be addressed to this topic to enable the construction of computer models for the description of peripheral blood flow under these conditions.

13.5 Computer modelling of the hunting reaction

It has been shown (e.g., chapter 11) that the hunting reaction varies tremendously between subjects. Several attempts were made to relate subject related factors to the hunting reaction. No relation was found for the age of the subjects, surface area of the hand, volume of the hand, body mass, stature, body surface area and subject specific threshold in core temperature for finger vasodilatation (chapter 9). All subjects in the hunting reaction experiments were male. There is no reason to assume that there are large differences in the amount of acclimatization of the fingers to cold between subjects. Therefore, no subject related variable could be identified that enabled an explanation for the variation in hunting reactions.
The experimentally induced body core and body skin temperature and the temperature of the water bath, however, are known to be related to the hunting parameters. Table 13.3 summarizes the body core temperature, mean body skin temperature and water bath temperature of the experiments in chapters 6 to 12, averaged over all subjects. A total of 58 subjects immersed at least one hand in cold water under various experimental conditions. The resulting finger skin temperature just before immersion and the hunting parameters T_{max}, T_{min} and onset time are also shown in Table 13.3. The esophageal or ear canal temperature was taken as the core temperature. If only rectal temperature was available, the core temperature was set to the rectal temperature minus 0.2°C.

Table 13.3 Core temperature (T_c), mean skin temperature ($\bar{T}_{sk}$), water bath temperature (T_w), mean finger skin temperature before immersion ($\bar{T}_{fi,imm}$), minimum finger skin temperature (T_{min}), maximum finger skin temperature (T_{max}) in °C and onset time in minutes.

chapter	T_c	$\bar{T}_{sk}$	T_w	$\bar{T}_{fi,imm}$	T_{min}	T_{max}	onset time
6			4.8	28.1	6.1	8.3	9.0
7	36.7		10.0	34.4	12.7	14.6	7.0
8	36.5	34.0	5.9	32.0	7.6	10.0	6.4
	36.8	34.4	6.0	33.0	9.4	12.2	5.1
9	36.8	33.3	9.2	30.6	10.0	12.3	9.1
	36.8	33.4	6.0	29.2	6.9	10.4	6.7
	36.8	34.2	10.0	32.5	11.2	15.0	10.5
	36.9	34.1	7.1	33.5	8.4	12.8	8.9
10	36.5	34.4	8.0	33.5	9.8	13.0	10.7
	36.6	27.0	8.0	19.3	8.7	9.5	18.9
	36.8	32.3	8.0	32.1	9.6	12.6	10.6
	37.1	34.9	8.0	35.3	11.3	17.0	3.0
	37.2	27.7	8.0	27.9	9.4	10.7	17.0
11	37.8	33.4	6.3	30.5	8.2	11.6	6.9
12	36.1	21.2	5.0	14.0	5.4	8.3	13.0
	36.8	31.8	5.0	32.0	6.9	11.0	7.2
	38.0	37.9	5.0	37.0	13.9	20.9	-

Due to the lack of subject related variables, only general recommendations (in the form of regression equations) can be given for computer modelling of the hunting reaction. Those equations are depicted below and are based on thermal status of the body and water bath temperature as shown in Table 13.3. The simulations based on these regression equations only indicate the expected average hunting reaction of a group of young males without local cold acclimatization and have no predictive value for a certain individual.

The mean finger skin temperature before immersion appeared to be mainly dependent on the mean skin temperature.

$$\bar{T}_{fi,imm} = 1.394 \cdot \bar{T}_{sk} - 14.8 \ (r=0.95) \qquad [13.1]$$

The minimum finger temperature appeared to be mainly dependent on the water bath temperature and the core temperature. The mean body skin temperature explains less variation.

$$T_{min} = 0.542 \cdot T_w + 2.004 \cdot T_c + 0.176 \cdot \bar{T}_{sk} - 74.32 \ (r=0.81) \qquad [13.2]$$

The maximum finger temperature appeared to be not dependent on the water temperature but only on the core temperature and the mean body skin temperature.

$$T_{max} = 2.533 \cdot T_c + 0.391 \cdot \bar{T}_{sk} - 93.61 \ (r=0.78) \qquad [13.3]$$

As discussed in chapters 10 and 12, the onset time is mainly determined by the mean skin temperature, and not by core temperature. The regression equation derived from Table 13.3 is:

$$\text{onset time} = -0.961 \cdot \bar{T}_{sk} + 1.528 \cdot T_w + 29.20 \ (r=0.89) \qquad [13.4]$$

13.6 Recommendations for further research

In the cold, the hands are prone to cold injury and to decreased dexterity because insulating the hands interferes with the tasks to be performed. Therefore, it is important to investigate methods for improvement of hand function and decrease the risk of cold injuries. Possible methods are:

- Application of extra heat. The location where extra heat should be applied is still debated and needs further research. Indirect heating of the torso has the advantage that the hands remain free for the task.
- Training for an improved hunting reaction. Acclimatization of the hands to cold is described in several publications. A standardized method to achieve optimal results still has to be devised. In this respect the method of Jobe et al. (1982), who repeatedly immersed the hands of subjects with Raynauds phenomenon in cold water, deserves more attention.

The mechanism responsible for CIVD is still subject to debate. The interaction between the axon reflex and sympathetic activity, as found by Hornyak et al. (1990) deserves more attention. Vascular visualization during CIVD may be a helpful tool to trace the vascular changes during CIVD.