Effect of direct neck cooling on psychological and physiological state in summer heat environment

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Abstract
To face the decrease of lifestyle comfort, the augmentation of hypothermia risks, and the deterioration of labor productivity resulting from energy consumption reduction policies, we have been proposing a wearable air-conditioning device worn like a scarf. This paper reports evaluation results of this wearable air-conditioning device’s effectiveness regarding comfort in hot summer office environment. We studied through trial subjects how neck cooling affects (1) subjective evaluation on comfort, thermic, and sweat sensations, and (2) human physiology when performing various deskwork tasks in summer heat environment. The environment of a typical Japanese office space in summer heat were reproduced using an environment control room. The environment control room’s temperature, humidity and wind velocity were set to re-create summer heat office environment (32°C, 60%, 0.15 m/s). 16 healthy subjects sat in the room in both normal condition and neck cooling condition. All subjects were dressed respecting the standard “cool-biz” dress code in Japan. (1) Comfort sensation, thermic sensation, and sweat sensation were evaluated by self-assessment. For all subjects, both discomfort sensation, heat sensation, and humidity sensation increased together with room temperature elevation, such we can understand that there is a clear correlation between environment temperature and comfort regarding temperature sensation. (2) Furthermore, we could quantitatively define the correlation between self-assessment, temperature variations, and physiological signals such as sweat amount and heart rate variability, by investigating the individual differences for comfort/discomfort in both normal and neck cooling conditions. Experimental results of this study show that using the wearable air-conditioning device in summer heat office, air-conditioner can be turned off or temperature set higher, without affecting comfort.

Key words: Wearable, Peltier element, Personal cooling, Thermic sensation, Sweat sensation, Comfort, Heart rate variability

1. Introduction

Today in Japan, comfortable lifestyle and environment realized by abundant electric power is being questioned by energy consumption reduction policies. In summer 2005, the Government of Japan, through the Agency for Natural Resources and Energy, started the “cool biz” campaign, which recommend setting room air-conditioner temperature to 28°C for energy-savings promotion. Though before “cool biz” start the average room temperature of about 16 thousands office buildings in Tokyo metropolitan area was 25°C, most companies respect this guideline. However, according to a survey carried out by Daikin Industries, Ltd. among 100 Japanese salarymen, 80% answered feeling too hot in such office
room condition, resulting in deterioration of labor productivity. Moreover, this has been accompanied by an augmentation of heatstroke risk due to not only hot but also humid summer in Japan. According to Japan Meteorological Agency, more than 70 summer days exceed a daily temperature of 30°C, while the average relative humidity is about 70%. When air temperature is 30°C and relative humidity 70%, the Wet Bulb Globe Temperature (WBGT, a measure of heat stress) is 29°C, which correspond to a state of strict vigilance according to the heatstroke prevention regulations.

Many researches on the effects of thermal stress deals with heat stress. Extreme temperatures or long exposure to less than ideal weather can change core body temperature and impact homeostatic control, or the body’s ability to maintain its temperature. As the body works harder to maintain a healthy core temperature by reallocating resources like water and energy, the brain is deprived of these same resources and one’s ability to think declines (Tomporowski et al. 2007). Several researches reported that both local cooling and warming affect physiological indices variations (Kaczmarczyk et al. 2004, Uebara and Xu 2004, Nagano et al. 2012). Head-neck cooling has already been demonstrated effective in several medical uses. Using a head-neck surface cooling garment, Wang et al. (2004) showed an average temperature reduction of 1.84°C in patients with severe brain injuries. The head-neck cooling technology may have beneficial effects on brain temperature in the athletic world when body temperature, and presumably brain temperature, are elevated (Lee et al. 2014, Wang et al. 2014). Recently, Jackson et al. (2015) demonstrated that head and neck cooling technology may represent a sensible, practical, and effective strategy to potentially enhance recovery of cognitive function after sports-related concussion. Also, neck cooling causes variations in brain temperature and brain blood flow (Gaoua et al. 2011, Kawahara and Katagiri 2012).

We have developed the intelligent neck cooler, a Peltier element based wearable device that directly cools human body (Kawakubo, et al., 2013). In a preliminary work, we have studied how neck cooling in hot climate affects warm-cold subjective sensation on a small number of subjects (Takahashi et al. 2012). Since, we have been investigating the effectiveness of direct neck cooling in summer conditions office environment. We studied through trial subjects how neck cooling affects (1) subjective evaluation on comfortable, thermic, sweat sensation, and (2) physiology environment.

2. Methods
2.1 Participants and experimental conditions

Our objective is the development of effective energy saving technology for direct temperature-conditioning of human body. We have developed a wearable equipment, the intelligent neck cooler, for individually adaptive temperature-conditioning based on human factors such as comfort and sense of fit. Since cool-biz policy is not satisfactory regarding comfort, nor sufficient regarding energy-savings (air-conditioner power consumption), we evaluated the effect of Effect of developed wearable equipment on psychological and physiological state in summer heat environment without air-conditioning. The environment of a typical Japan summer heat can be reproduced using an environment control room as shown in Fig. 1, in which temperature and humidity can be set and controlled in detail (see Fig. 2). Concretely, the environment control room temperature and humidity were respectively set at 32°C and 60%, which correspond to a WBGT of 29°C, for both experiments with and without wearing neck cooler. Considering health risk in such conditions, participants to the experimental were selected among volunteer young adults. Written consent was obtained from 16 subjects, eight men and eight women from twenties to thirties. All subjects were healthy, wearing underwear, a full-length pants, and a short-sleeved shirt without neck-tie (standard “cool-biz” dress code in Japan).

Subjects were sat in the room, performing an experimental procedure of about two hours (see Fig. 3). The procedure begins with a phase at rest of 30 minutes accommodating to the room environment. Then they performed successively three tasks of 15 to 20 minutes that have been chosen to simulate conventional deskwork: S-A creativity test to evaluate creative work performance (Tokyo Shinri Corp. 1969), Conners’ Continuous Performance Test (CPT) X task to evaluate attention keeping during work, and CPT AX task to evaluate work memory performance (Corkum & Siegel, 1993). The procedure ends with a 10 minutes phase at rest (cool-down). Each subject performed the experiment once using the neck cooler, and another time in normal condition (not using neck cooler). The device’s neck part temperature was fixed at 18°C at the start of each experiment, though we took into account preferences regarding heat and coolness, and indicated the subjects they could increase the temperature or switch the device’s power on/off whenever they want during the experiment. The device’s neck part temperature could be switched in seven steps from 18°C and 28°C. Except for the few seconds to reach the target temperature after starting, the maximum device’s power consumption was less than 20W during the experimental for all subjects (total average 12.5W, subjects’ maximum 18.2W, subjects’ minimum 6.4W).
During the experiment, comfort/discomfort sensation, thermic sensation, and sweat sensation were evaluated at regular intervals using both self-assessment by a Visual analog scale (VAS) and physiological information measurement (sweat, heart rate variability). Thermic sensation scale ranges from 0 for cold sensation to 10 for hot sensation. Sweat sensation scale ranges from 0 for dry sensation to 10 for humid sensation. In the same way, comfort/discomfort scale ranges from 0 for discomfort to 10 for comfort (see Fig. 4). Thermic sensation, sweat sensation, and comfort/discomfort sensation were self-assessed 30 minutes after entering the room and after each task using VAS.

All results presented in sections 3 and 4, were validated using Welch's t-test. It is a statistical hypothesis test used to determine if two sets of unequal variance data sets are significantly different from each other.

![Fig. 1. Environment control room.](image1.jpg)

![Fig. 2. Temperature and Humidity in the environment control room during the experiment](image2.jpg)

![Fig. 3. Experimental procedures and schedule](image3.jpg)

![Fig. 4. VAS used for evaluation of sweat sensation, thermic sensation, and comfort/discomfort feeling](image4.jpg)
2.2 Cooling device

Among researches cited in introduction, several solutions have been used to cool the head or neck. Mostly, they use ice to cool a water circulating based system such as in Jackson et al. (2015), whose device is based on the Welkins EMT Temperature Management System (Welkinmed, Downers Grove, IL, USA), connected to an original pneumatic head-neck unit they engineered. In their cold condition experimental, the Welkins EMT unit was set to maximum cool and a frozen ice pack was placed into the unit, such the temperature of water circulating in the cooling helmet was maintained at 4°C. However, beyond this device not being designed for use in daily life, head-neck unit temperature cannot be set in detail, nor be controlled during use. Wearable solutions have been proposed for military applications such RINI Technologies’ Light-Weight Environmental Control System (LWECS), which claim being the smallest, lightest and most efficient personal cooling solution ever developed. The LWECS employs patented technology in a vapor compression cycle to chill water to 22°C that circulates through a Cooling Vest that is worn close to the skin. However, it weighs 3kg and vest’s temperature neither can be set other than 22°C nor can be regulated during use. Recently, Thanko Inc. released a very small size (65x40x35mm) and lightweight (60g) portable USB-powered Peltier element cooling system. Though Peltier element’s temperature is assumed to reach a minimum of 15°C with an average of 22°C, temperature variations during use cannot be controlled, nor can the average temperature.

We have developed the intelligent neck cooler, a Peltier element based wearable device that directly cools human body (Kawakubo, et al., 2013). The device weighs less than 650 grams and its maximum power consumption is less than 27.95W. Three Peltier elements are placed in the neck worn part of the device that is capable of regulating linearly user’s neck temperature between 18°C and 28°C (see Fig. 5). It also embeds sensors measuring neck part temperature, as well as surrounding temperature and humidity. When applying a voltage across the Peltier element, as a result, a difference in temperature is built up between the two sides. Controlling the direction of the electric current enables to cool-down the side fitting to the skin, such cooling directly the body. The opposite side of the Peltier element is proportionally heating, such a water cooling circuit (tubes and radiator) is necessary. Peltier elements’ temperature at neck is controlled by sensor readings of air temperature and humidity, and neck temperature to prevent from over heating and cooling. The device embeds a micro-controller that can autonomously regulate neck part temperature through a patented algorithm using a bi-linear equation of temperature and humidity to estimate the discomfort index (Wada et al 2013). Fig. 6 shows schematics of the device’s attachment (left) and mechanism (right). The device’s detailed specifications are summed-up in Table 1.

![Fig. 5. Photograph of the device’s neck part with detailed description of its composition](image-url)
3. Neck cooling effect on comfort level and thermic sensation
3.1 Evaluation of effect on comfort level

We compared the VAS self-assessment of the 16 subjects for comfort/discomfort sensation in both normal and neck cooling conditions 30 minutes after entering the environment control room. More than 80% of the subjects self-assessed a higher comfort level in neck cooling condition (see Fig. 7 left).

Moreover, one-tailed t-test confirmed statistical significance ($P(T < t) = 0.001$) of better comfort level in neck cooling conditions. Statistical significance could also be confirmed ($P(T < t) = 0.029$) for neck cooling positive effect on comfort sensation when performing deskwork task, such as S-A Creativity test (see Fig. 7). Though statistical significance could not be confirmed after CPT-X and CPT-AX test, neck cooling tends to have a positive effect on comfort sensation also when performing deskwork task. Though comfort level of subject K is strongly declining in neck cooling condition, we can reasonably consider this is due to specific case of persons who usually feel comfortable even in summer heat condition such the highest self-assessment suggests it.
3.2 Evaluation of effect on thermic sensation

We compared the VAS self-assessment for thermic sensation (cold/hot) of the 16 subjects in both normal and neck cooling conditions. More than 85% of the subjects self-assessed a colder sensation in neck cooling condition. Moreover, one-tailed t-test confirmed statistical significance of lower thermic sensation level in neck cooling condition, both after accommodation phase ($P(T<t) = 0.001$), and after S-A Creativity test ($P(T<=t) = 0.053$), as shown on Fig. 8. These results confirm the positive thermal effect of neck cooling in summer heat office environment, whatever the activity is.

3.3 Evaluation of effect on sweat sensation

Third, we compared the VAS self-assessment for sweat sensation (dry/humid) of the 16 subjects in both normal and neck cooling conditions. More than 85% of the subjects self-assessed a drier sensation in neck cooling condition. Moreover, one-tailed t-test confirmed statistical significance of lower sweat sensation level in neck cooling condition,
both after accommodation phase \( (P(T<t) = 0.001) \), after S-A Creativity test \( (P(T<=t) = 0.053) \), and after CPT-X test, as shown on Fig. 9. Only subjective assessment after CPT-AX task, could not confirming the positive effect on humidity sensation of neck cooling in summer heat office environment.

4. Neck cooling effect on physiology
4.1 Evaluation of sweat amount

Sweat amount were measured during the whole experiment every two seconds by difference method using a ventilated capsule-type sweat sensor (SNT-200, Rousette Strategy Inc., Fig. 10 left). Measurement error occurred for two subjects due to sensor electrodes detachment because of excessive sweating, such we compared the average sweat amount during the whole experiment for 14 subjects, when neck cooling was performed or not (See Table 2).
Sweat amount was slightly lower when neck cooling was performed (Table 2). Fig. 11 shows an example of sweat amount variations during the experimental for the same subject wearing or not the neck cooler. We can observe not only a lower sweat amount, but also larger sweat amount variations in neck cooling conditions. As shown on Fig. 12, though individual differences exist, for 9 subjects among 14 average sweat amount during the whole experimental was lower in neck cooling condition. Also, sweat amount variation was larger in neck cooling condition for 11 subjects among 14. One-tailed t-test confirmed statistical significance ($P(T\leq t) = 0.06$) of both lower average sweat amount and larger sweat amount variance in neck cooling condition.

![Sweat sensor (left picture) and Heart rate sensor (right picture)](image)

**Table 2 Comparison of the effect of neck cooling on sweat amount during the experiment**

<table>
<thead>
<tr>
<th></th>
<th>Average sweat amount [g/m²/min]</th>
<th>Sweat amount variance [g/m²/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck cooling</td>
<td>17.04</td>
<td>6.41</td>
</tr>
<tr>
<td>No Neck cooling</td>
<td>18.02</td>
<td>2.01</td>
</tr>
</tbody>
</table>

![Sweat amount variations during the experiment wearing or not the neck cooler (case of subject B)](image)
4.2 Evaluation of heart rate variability

Heart rate variability beat by beat during the whole experiment using a wearable 2-leads electrocardiograph (myBeat, Union Tool co., Fig. 10 right), which can automatically extract and log in real-time heart beat timing from electrocardiogram signal. The evolution of heart rate variability as sympathetic nervous system activity index, and comfort/discomfort by VAS evaluation have been compared. Ratio of consecutive heart rate intervals (RRI) that difference is greater than 50 milliseconds (PNN50) was used as sympathetic nervous system activity index. A high PNN50 ratio represents a state when the activity of parasympathetic nervous system is dominant compared to sympathetic nervous system.

Average PNN50 ratio was calculated every five minutes during the whole two hours experiment, such obtaining 24 samples. Each sample is the average PNN50 of all 16 subjects during the same 5 minutes period of the experiment, such the analysis result is independent from the subject. Fig. 13 shows that when comfort level assessment is high, PNN50 ratio is also high with an acceptable correlation of 0.57. Fig. 14 shows also that PNN50 ratio is significantly higher when performing neck cooling, such demonstrating a better comfort level (P(T>t) = 0.01).
5. Conclusion

We evaluated through trial subjects’ experiments how neck cooling affects psychology and physiology in summer heat environment. More than 80% of 16 subjects reported significantly better comfort level ($P(T>t) < 0.05$) in neck cooling condition. Heart rate variability index PNN50 reflected significantly higher values when performing neck cooling, showing to be a promising index for real-time assessment of thermic comfort level at rest or during deskwork tasks.

We could observe that both hot thermic sensation and skin sweat sensation are directly affected by neck cooling, becoming lower. We could also observe about sweat amount that although subjects were in continuous sweating state in usual summer heat environment, sweating was intermittently inhibited by neck cooling. Such, we can assume these changes in hydro-thermic sensations and physiology have a strong influence on comfort level improvement, which were also verified by Heart rate variability index PNN50 variations indicating more parasympathetic nervous system activity.
in neck cooling condition.

So far, many studies have evaluated qualitatively the effect of head or neck cooling on performance, attention, as well as some medical issues. In relation, the only studied physiological indices have been core temperature, or brain activity. This study is the first to raise the issue of hydro-thermic and comfort sensations, both on qualitative and quantitative approaches. The following two scientific discoveries have been demonstrated through experimental on 16 healthy subjects in simulated summer heat conditions.

1. Not only sweat amount, but also sweat amount continuous variations have a strong impact on sweat sensation (from sweat sensation assessment in section 3.3 and sweat amount analysis in section 4.1).
2. Adaptive neck cooling has a direct effect of lowering sympathetic nervous system activity, resulting in better thermal comfort (from hedonic sensation assessment in section 3.1 and HRV analysis in section 4.2).

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References


