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ORIGINAL ARTICLE

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Thermal properties of interior decorating material and the sensation of cold/warm by contact II: the relations among heat flux, temperature change of material, and sensation of cold/warm by contact

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Abstract The main purpose of this study was to investigate the changes in heat flux and temperature after the subject's palm was in contact with interior decorating materials. The relations among heat flux, temperature, and sensation of cold/warm during contact were studied. Ten men and ten women were selected and introduced to 21 materials for the contact test. They were in contact with the specimens for 30 min without seeing them in a climate-controlled room at 25° ± 1°C and 65% RH. Changes in the heat flux and temperature of the specimens were determined by a heat flux meter. A sensory evaluation test was applied to evaluate the cold–warm contact. Results indicated that the heat flux and temperature increased with increasing time after the subject's palm was in contact with the specimens. The heat flux (Q_{30}) and temperature (T_{30}) 30 min after the subject's palm contacted the specimens were greater for male subjects than for female subjects. A positive linear regression equation existed between the values for Q_{30} and T_{30}, whereas a negative linear regression formula existed the sensation of cold–warm by contact (S) and the values of $ln(Q_1 \cdot \lambda)$. Therefore, the sensation of cold/warm by contact could be estimated simply by using the thermal physical properties of the interior decorating materials.

Key words Interior decorating material · Change of skin temperature · Contact sensation of cold/warm · Physiological value · Thermal osmotic coefficient

Introduction

According to our previous report,[1] the fingertip maximum dropping temperature (T_d) of the physiological response was closely related to the specific gravity (ρ_u) and thermal conductivity (λ) of materials. The psychological sensation of cold–warm during contact (S) had positive linear relations with fingertip maximum dropping temperature (T_d) and the product of ($T_d \cdot \lambda$). However, the sensation of cold–warm (S) had a negative linear relation with the thermal osmotic coefficient (b). Therefore, the psychological sensation of cold–warm could be evaluated by the maximum fingertip dropping temperature of the physiological response and the basic properties of the material.

This study was based on the relation between the change of heat flux after the palm contacts the material's surface and the psychological sensation of cold–warm. The effects of the thermal properties on the sensation of cold–warmth during contact were studied. The results provided basic information for the selection and evaluation of interior decorating materials.

Testing materials and methods

Testing materials

The 21 interior decorating materials and the twenty 20- to 30-year-old subjects were the same as those in the first report.[1] All materials were cut into 30 cm (length) × 20 cm (width) thin plates. The thickness of the solid wood and the wood-based material specimens were 1 cm, and the thickness of the other material was their original thickness (0.8–1.7 cm). Material properties including thermal conductivity are noted in Table 1.

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Table 1. Physical properties of 21 interior decorating materials

Specimen	Thickness, h (cm)	Specific gravity, ρ	Thermal conductivity, λ (kcal/mh °C)	Specific heat,[a] C (kcal/kg °C)	Thermal Diffusivity, α (m^2/h)
Solid wood					
Taiwania	1.0	0.36	0.202	0.379	1.481×10^{-3}
China fir	1.0	0.31	0.149	0.379	1.268×10^{-3}
Taiwan red cypress	1.0	0.39	0.196	0.379	1.326×10^{-3}
Taiwan paulownia	1.0	0.22	0.122	0.379	1.463×10^{-3}
Hard maple	1.0	0.56	0.222	0.379	1.046×10^{-3}
Red oak	1.0	0.62	0.236	0.379	1.004×10^{-3}
Red meranti	1.0	0.52	0.209	0.379	1.060×10^{-3}
Teak floor	1.0	0.66	0.201	0.379	8.036×10^{-4}
Red cypress floor	1.0	0.45	0.128	0.379	7.505×10^{-4}
Wood-based materials					
Fancy plywood (red oak)	1.0	0.65	0.141	0.379	5.724×10^{-4}
Fancy plywood (red cypress)	1.0	0.55	0.115	0.379	5.517×10^{-4}
Particleboard	1.0	0.62	0.233	0.379	9.916×10^{-4}
Fiberboard	1.0	0.59	0.172	0.379	7.692×10^{-4}
Insulation board	0.9	0.15	0.245	0.379	6.157×10^{-4}
Inorganic material					
Gypsum	0.9	0.89	0.245	0.230	1.197×10^{-3}
Tile	0.8	2.14	0.998	0.220	2.120×10^{-3}
Marble	1.0	2.64	2.396	0.209	4.342×10^{-3}
Ground floor	1.7	2.50	0.650	0.220	1.182×10^{-3}
Glass	1.0	2.32	0.872	0.937	4.011×10^{-4}
Others					
PS foam	1.2	0.08	0.190	NA	NA
Rabbit fur	0.1	0.25	0.243	NA	NA

[a] Specific heat was obtained from references 6 and 7

Measurement of heat flux and temperature of specimen

Although heat transfer is a three-dimensional phenomenon, the heat transfer model for palm-contacted material can be treated as one-dimensional.[2] With the subject's palm on the surface of specimens, as shown as Fig. 1, the area of the heat transfer system is A (cm^2), the thickness of the specimen is L (cm), and the temperatures on the two sides of the specimens are the palm temperature, T_A (°C), and the heat flux meter temperature, T_B (°C). The environmental temperature is T_{B_0} (°C). T_B is a function of time. If the heat transfer system is at steady state, the heat flux (Q) from the palm through the specimen can be expressed as follows.

$$\frac{dQ}{dt} = -\lambda \cdot A \cdot \frac{T_B - T_A}{L} \qquad (1)$$

where λ is the thermal conductivity of specimens. In Eq. (1), if $L = \Delta X, 0$ and $\Delta T = (T_A - T_B), 0$, it can be expressed as follows.

$$\frac{\partial Q}{\partial t} = -\lambda \cdot A \cdot \frac{\partial T}{\partial X} \qquad (2)$$

Generally, λ is a constant. Suppose the mass of the specimen is m (g) and the specific heat is C (cal/g °C), heat flowing into the heat flux meter per unit time is expressed as follows.

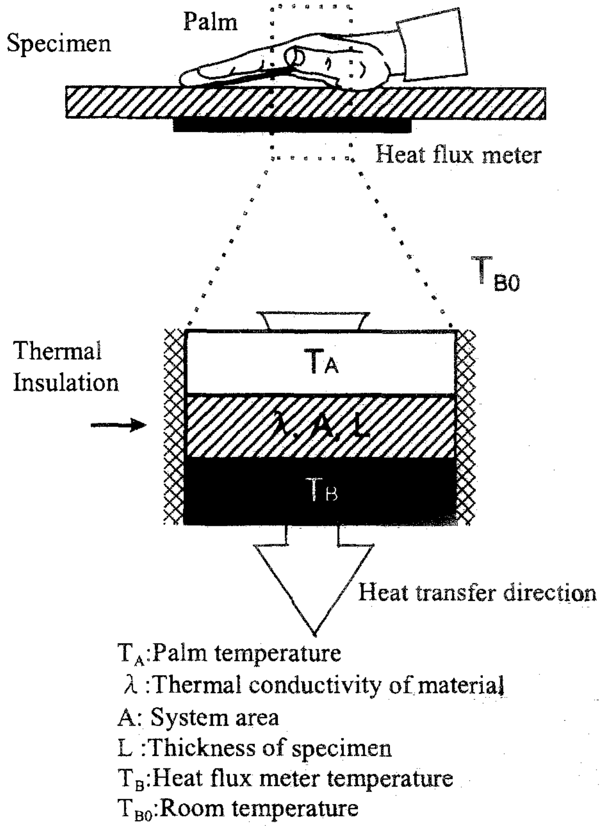

Fig. 1. One-dimensional heat transfer model of experiment for sensation of cold–warm during contact

$$\frac{dQ}{dt} = m \cdot C \cdot \frac{dT_B}{dt} \qquad (3)$$

From Eqs. (1), (2), and (3) we derive the following equation.

$$m \cdot C \cdot \frac{dT_B}{dt} = \lambda \cdot A \cdot \frac{T_A - T_B}{L} \qquad (4)$$

Reorganizing Eq. (4) yields:

$$\frac{dT_B}{T_A - T_B} = \frac{\lambda \cdot A}{m \cdot C \cdot L} \cdot dt \qquad (5)$$

Set $\frac{\lambda \cdot A}{m \cdot C \cdot L} = Z$ as a constant; then integrate Eq. (5).

$$\int_{T_{B_0}}^{T_B} \frac{dT_B}{T_A - T_B} = \int_0^t Z \cdot dt \qquad (6)$$

$$\ell_n\left(\frac{T_A - T_B}{T_A - T_{B_0}}\right) = -Z \cdot t \qquad (7)$$

or

$$\left(\frac{T_A - T_B}{T_A - T_{B_0}}\right) = e^{-Z \cdot t} \qquad (8)$$

that is

$$T_B = T_A - \left(T_A - T_{B_0}\right) \cdot e^{-Z \cdot t} \qquad (9)$$

A Kemtherm HFM-115 multiple points heat flux meter (Kyoto Electric K.K. product) was used for this experiment. It is equipped with 15 recording channels that recorded the surface temperature of the specimen and the heat flux of the unit area.

The heat flux sensor (Sensor ER2-L) was attached to the bottom surface of the specimen. After the subject's palm contacted the specimen, the change of heat flux and temperature of the specimen were recorded once every 30s for 30min, as shown in Fig. 1.

Sensation of cold/warm during contact

A test method based on the paired comparison method and the rating method was applied to the cold/warmth sensation experiment on the human hand because it is simple and gives clear results. The method was designed to compare materials that could not be sorted at once. Two materials were chosen for a comparison test. After mC_2 times of testing, all material could be sorted for the final results.

First, the subject must sit quietly in a climate-controlled room [25°C and 65% relative humidity (RH)] for 5min. Then both hands are placed on the surfaces of two specimens for 30min. For the experiment to be unbiased, the test specimens are then placed in a covered box. The sensory sensitivity was reduced after long durations of stimulation, a phenomenon called sensory adaptation. Thus, the sensation of cold/warmth during contact was recorded after oral inquiry when the subject had been in contact with the specimens for 10s. The five grades of cold/warm sensation were very cold (1 point), cold (2 points), chilly (3 points), cool (4 points), and warm (5 points). For example, 2 points for a specimen might be recorded for the right palm and 3 points for the left. After all the specimens were tested, the sensation of cold/warm and its standard deviation (SD) were calculated. In other words, if there were m specimens and N subjects, the psychological sensations of the contacted material was based on $N(m-1)$, giving the average and SD. The change in the specimens' temperatures and heat fluxes were measured during the experiment.

Results and discussion

Heat flux properties of specimens

Because the skin surface temperature of the human body is about 34°C, which is higher than the specimen temperature (25°C), the palm is treated as a heat source, with heat transferring from palm to specimen because of the temperature difference. Heat flux was measured by a heat flux meter affixed to the bottom of the specimen.

In this experiment, the results showed that heat flux increased gradually with time after the palm contacted the specimen, although a tendency to decrease was found in some specimens at the end of the experiment. The increasing tendency depended on the subject's gender and the material tested. Heat flux was noted at 30min, as shown in Table 2; and the values for men were higher than those for women. The F-test indicated that materials showed a significant gender difference except China fir, Taiwan red cypress, fancy plywood of red oak with polyurethane resin (PU) coating, teak solid wood floor with PU coating, particleboard, marble, glass, and polystyrene foam. This finding may be due to the metabolism of men being more active than that of women.

Generally, heat flux increased with increasing thermal conductivity (λ), but it did not show this relation at 30min (Q_{30}). Although inorganic materials such as tiles, marble, and ground floor had large λ values, their heat flux did not increase proportionally. The reason could be that because of the large heat capacity of the material it stored heat and did not immediately transfer it to the heat flux meter at the bottom of the specimen.

To eliminate the influence of the heat capacity difference of materials, the heat flux at the first minute (Q_1), or the instant heat flux at the first minute, was measured. The results showed that Q_1 increased with an increase in λ, but the relation was varied because most specimens were wood and wood-based material. Obviously, the Q_1 value for MDF, gypsum board, tiles, marble, glass, and rabbit fur were higher than those for other wood and wood-based materials.

Sakuragawa et al.[3] also undertook sensory cold/warm tests of floor. Their results indicated that after the palm

Table 2. Results of *t*-test for difference between male and female contacts with 21 interior decorating materials at various conditions

Specimen	Heat flux at 1 min (W/m^2), Q_1		Heat flux at 30 min (W/m^2), Q_{30}		Temperature increase of material after 30 min, T_{30} (°C)	
	Male	Female	Male	Female	Male	Female
Solid wood						
Taiwania	1.3	0.9	32.6*	28.2	3.8	4.0
China fir	0.7	0.6	31.9	27.6	4.4	3.8
Taiwan red cypress	1.0	1.1	32.8	25.6	3.9	3.5
Taiwan paulownia	1.2	1.5	33.9*	29.7	4.5	3.6
Hard maple	0.5	1.1	33.9*	33.7	4.8	4.6
Red oak	1.5	1.0	36.2*	31.8	4.6	4.2
Red meranti	0.5	0.9	33.5*	30.4	4.3	4.4
Teak floor	0.3	0.4	37.9	34.2	4.9	3.9
Red cypress floor	0.7	1.0	33.7*	28.9	5.1	3.8
Wood-based materials						
Fancy plywood (red oak)	0.3	0.2	33.9	24.9	4.8	3.5
Fancy plywood (red cypress)	0.7	1.3	38.3*	28.1	4.6	3.9
Particleboard	0.9	0.3	38.0	34.3	4.8	4.1
Fiberboard	0.5	0.9	35.1*	32.0	4.8	4.2
Insulation board	7.4	6.7	32.2*	25.9	4.8	3.7
Inorganic material						
Gypsum	12.6	7.2	51.1*	34.2	6.7	5.0
Tile	8.8	9.7	42.8*	37.7	5.6	4.6
Marble	11.7	9.3	39.3	29.6	6.1	4.1
Ground floor	0.8	0.5	28.1*	19.3	3.5	2.3
Glass	11.9	10.3	52.8	48.6	6.3	5.8
Others						
PS foam	1.5	1.3	20.6	18.1	2.6	2.6
Rabbit fur	45.3	41.9	54.2*	40.3	6.4	4.8

* Significant difference between males and females

contacted the specimens the heat flux increased rapidly and reached a maximum at 50s; it then decreased slightly and remained constant. That tendency was somewhat different from the results of this study, which could be because they affixed the sensor (Kemtherm HFM, MA, EM) to the inside of the palm and then established contact with the surface of the specimen; the bottom of the material was spread with mortar. This is totally different from when the sensor is affixed to the bottom of the specimen. Thus, in their study heat flux was less influenced by heat capacity. They also indicated that the maximum heat flux ($q_{\max}$) and heat flux at 10 min (q_{10}) of the palm-contacted materials decreased in the order: steel > plywood > styrofoam. Hence, the higher thermal conductivity of materials is associated with a larger heat flux. The palm temperature was influenced by personal differences, such as physiological and psychological conditions and the environment. Although the heat flux varied, $q_{\max}$ and q_{10} were important indicators for evaluating the cold/warm sensation of materials during contact.

Temperature change of specimens

The specimen temperature gradually increased with an increase in contact time. At the end of the experiment the temperature of solid wood, wood-based materials, and inorganic materials rose 3.5°–4.8°C, 3.5°–5.1°C, and 2.3°–6.7°C, respectively. The results were caused by the heat flux of the palm. Other then taiwania, red meranti, and styrofoam, the rise in temperature was greater when induced by men than by women. The results consisted in a heat flux tendency. The *t*-test results of increasing temperature are shown in Table 3. The relations between the heat flux at 30 min and the temperature increase on the material's surface could be represented by positive linear regressions. Their coefficients of determination (R^2) were significantly different at the 0.01 confidence level by *F*-test, summarized as follows:

$$T_{30} = 0.113Q_{30} + 0.607 \qquad R^2 = 0.869 \quad F = 265.5^{**}$$

Heat transfer model of specimen

According to Eq. (7), experimental data were substituted as follows.

$$\ln\frac{(\text{palm temperature} - \text{room temperature})}{(\text{palm temperature} - \text{heart flux meter temperature})} = \varDelta T$$

that is,

$$\ell_n\left(\frac{T_A - T_{B_0}}{T_A - T_B}\right) = \varDelta T \tag{10}$$

Table 3. Results of *t*-test for time delay between male and female palm contacts with interior decorating materials; their determination coefficient for time-delay regressive equations

Specimen	Delay time (min)		Determination coefficient (R^2)	
	Male	Female	Male	Female
Solid wood				
Taiwania	−4.80	−0.22	0.977	0.952
China fir	−2.78	5.91	0.977	0.977
Taiwan red cypress	4.67	−4.79	0.962	0.979
Taiwan paulownia	2.29	−1.68	0.958	0.984
Hard maple	−3.25	−0.40	0.977	0.970
Red oak	2.41	−0.35	0.971	0.954
Red meranti	1.82	1.35	0.976	0.989
Teak floor	−1.40	−3.29	0.975	0.980
Red cypress floor	−1.39	−2.93	0.952	0.983
Wood-based materials				
Fancy plywood (red oak)	−3.87	−5.04	0.986	0.995
Fancy plywood (red cypress)	−1.04	1.00	0.983	0.974
Particleboard	1.52	−5.33	0.986	0.994
Fiberboard	3.19	−1.81	0.971	0.988
Insulation board	4.97	4.24	0.902	0.939
Inorganic material				
Gypsum	5.60	1.88	0.924	0.947
Tile	0.42	0.75	0.953	0.959
Marble	3.83	4.29	0.962	0.983
Ground floor	−4.65	−6.25	0.993	0.989
Glass	2.20	1.20	0.965	0.970
Others				
PS foam	3.19	−6.27	0.968	0.962
Rabbit fur	8.24	11.00	0.977	0.945

where ΔT is regression of time.

$$\Delta T = -a - ct = -c(t - x) \tag{11}$$

$$\text{hence, } x = -a/c \text{ (min)} \tag{12}$$

According to the one-dimensional heat transfer theory, the material temperature should rise immediately after the palm contacts the specimen; however, the heat flux meter did not immediately react and delayed x min ($x = -a/c$), which might be called the "delay time." The cause may be due to the sensitivity of the heat flux meter, the varied heat capacities of materials, or experimental error.

The R^2 values of the above regression were higher than 0.90, as shown in Table 3. Thus the one-dimensional heat transfer model is suitable for this experiment. Theoretically, the value c should relate to the sensation of cold/warmth (S), but, there was no significant relation between either the a value or the c value with S. Further studies are needed.

Heat flux and sensation of cold/warm during contact

Figure 2 shows that the change in heat flux after the palm contacted three interior decorating materials, including tile, taiwania, and sponge, with different thermal conductivities. It was found that the heat flux increased with contact time; the tendency to increase was significant for specimens with high thermal conductivities (λ), as was the heat flux at 1 and 30 min (Q_1 and Q_{30}). With the palm in contact with the specimen there was a large heat flux between the two and psychologically it felt cooler. However, when analyzing the relation between Q_1 and S, the heat flux at 1 min (Q_1) did not have a significant relation with the sensation of cold/warmth (S).

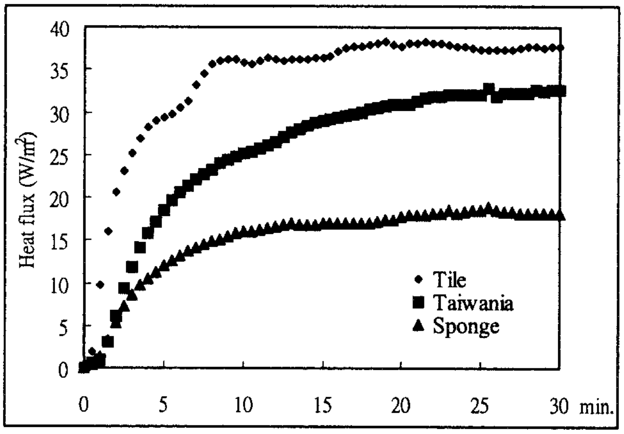

Fig. 2. Change of heat flux during contact with tile, taiwania, and sponge

Suppose that the instant heat flux at 1 min (Q_1) was influenced by the thermal conductivity (λ), Q_1 multiplied by λ. The results show that the higher is $Q_1 \times \lambda$, the lower are the cold/warmth points, or the cooler the specimen is. These relations can be summarized as follows:

$$S = -0.158\ln(Q_1 \times \lambda) + 2.423 \qquad R^2 = 0.231 \quad F = 12.0^{**}$$

The F-test results showed that the regression of the sensation of cold/warmth (S) and the natural logarithm of ($Q_1 \times \lambda$) was significant at the 0.01 confidence level. This is similar to the results reported by Okajima.[4] He indicated that the heat flux of red meranti was low and ranked as a "warm" material; aluminum and stainless steel, with a larger heat flux, were ranked as "cold" materials. This also agrees with our previous report.[5] Sakuragawa et al.[3] indicated there was negative relation between the sensation of cold/warmth (S) and the logarithm of the heat flux ($\log Q$). This means that the heat flux between palm and specimen is an important indicator for the sensation of cold/warm (S). The difference with their and our results was that the sensor was affixed inside the palm in Sakuragawa et al.'s experiment, not under the specimen as in our study; thus, heat flux was therefore less influenced by heat capacity.

Thermal diffusivity and sensation of cold/warm during contact

It is known that heat transfer is governed by the heat equation

$$\frac{\partial u}{\partial t} = \alpha\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)$$

which gives the temperature $u(x,y,z,t)$ in a body of material. Here α is the thermal diffusivity, which can be expressed as follows.

$$\alpha = \frac{\lambda}{C \cdot \rho_u} \tag{13}$$

where λ refers to the thermal conductivity of the material, C refers to the specific heat, and ρ_u refers to the specific gravity. The α values of 21 materials are given in Table 1. An analysis of α or $\ln\sqrt{\alpha}$ with S did not show a good relation. The results are consistent with those of Harada et al.[8] and Okajima et al.[8] Harada et al.[8] investigated the sensation of cold/warm during contact and indicated that a significant negative relation existed among the psychological value (S), thermal conductivity (λ), $\log \lambda$, thermal capacity ($C\rho$), and $\log C\rho$. In contrast, the relation between S and $\alpha(= \lambda/C\rho)$ was not significant. Okajima et al.[6] also indicated there were some problems estimating the S value from the α value, considered the physical characteristics of the material, which meant that α was not an important indicator for the sensation of cold/warm during contact. In the previous report[1] the S value had a significant negative relation with the thermal osmotic coefficient, b ($= \sqrt{\lambda \cdot C \cdot \lambda}$), which meant that the thermal properties (λ, C, ρ) were good indicators of the sensation of cold/warm during contact.

Considering all the experimental factors, including the materials' thermal properties of λ, C, and ρ, statistical analysis was done by stepwise regression. It showed that the coefficients of λ, C, and ρ were significant at the 0.01 confidence level. The sensation of cold/warm (S) can be expressed exponentially as follows.

$$S = 0.338\,\rho^{-0.128} \cdot \lambda^{-0.248} \cdot C^{-0.133} \qquad R^2 = 0.546 \quad F = 150.6^{**}$$

It can be concluded that the factors that influence the sensation of thermal properties of a material during contact are $\lambda > C > \rho$, according to the absolute values. This also means that only the thermal properties of material are enough to predict the sensation of cold/warm during contact.

Conclusions

1. The heat flux at 30 min (Q_{30}) is higher in men than in women. The one-dimensional heat transfer model is appropriate for the experiment.
2. The temperature of material gradually increased with the increase in duration of palm contact. At the end of the experiment, the temperature of solid wood and wood-based materials and of inorganic materials rose 3.5°–5.1°C and 2.3°–6.7°C, respectively. The temperature rise was higher for men than for women.
3. The relation between the heat flux at 30 min (Q_{30}) and the temperature increase at 30 min (T_{30}) can be represented by a positive linear regression formula.
4. The relations between the sensation of cold/warm (S) and the natural logarithm of ($Q_1 \times \lambda$) can be represented by a negative linear regression formula at the 0.01 significance level. Therefore thermal properties of materials may be considered indicators when assessing the sensation of cold/warm during contact.
5. The material thermal property coefficients λ, C, and ρ are excellent indicators for predicting sensation of cold/warm during contact without considering other factors.

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