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Combining colour and temperature: A blue object is more likely to be judged as warm than a red object

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It is commonly believed that reddish colour induces warm feelings while bluish colour induces cold feelings. We, however, demonstrate an opposite effect when the temperature information is acquired by direct touch. Experiment 1 found that a red object, relative to a blue object, raises the lowest temperature required for an object to feel warm, indicating that a blue object is more likely to be judged as warm than a red object of the same physical temperature. Experiment 2 showed that hand colour also affects temperature judgment, with the direction of the effect opposite to object colours. This study provides the first demonstration that colour can modulate temperature judgments when the temperature information is acquired by direct touch. The effects apparently oppose the common conception of red-hot/blue-cold association. We interpret this phenomenon in terms of "Anti-Bayesian" integration, which suggests that the brain integrates direct temperature input with prior expectations about temperature relationship between object and hand in a way that emphasizes the contrast between the two.

It is a long-held belief that reddish colours induce warm feelings while bluish colours induce cold feelings[1–5]. Such an association is a common practice in the fields of interior and industrial design and has been shown to influence people's impressions of the environmental thermal conditions[6–9] and produce warm or cold feelings even without physical presentation of thermal stimuli[10–12].

In most of the previous studies on colour-temperature perceptual interactions, the temperature information was presented to the participants in an indirect, non-contact fashion. Although direct manual exploration is the most intuitive and natural way for people to obtain veridical temperature information of the external world, few studies have addressed the effect of colour on perceived temperature of touched objects. An exception is an old report by Mogensen and English[13], in which participants touched two cylinders wrapped in different coloured papers and judged which seemed the warmer. Although Mogensen and English showed some effects of colour on temperature judgments (e.g., green was more likely to be judged to be warm than purple), their results did not lead to a clear conclusion as to how red and blue colours influence temperature judgments.

The first purpose of this study was to understand whether object and hand colours, particularly the representative red and blue, could have an impact on object temperature perception during hand-object interactions. When a hand touches an object, the temperature information acquired upon contact arises from changes in skin temperature, which in turn depends on not only the object temperature but also the hand temperature[14]. Accordingly, in the present study, we manipulated either the object colour (Experiment 1) or the hand colour (Experiment 2) while participants made contact with the object. We had the participants judged whether the object felt warm or not and varied the temperature of the object surface adaptively based on the participants' responses to determine the lowest temperature required for the object to feel warm. If red and blue colours have different impacts on temperature judgments, we expected the lowest warm temperatures would be different between the two colours.

In light of recent advancements in multisensory research, it is important to know not only *whether*, but also *how* colours affect temperature perception. It has been suggested that our brain can integrate tactile information with visual information in two opposite ways. When estimating the size or surface roughness of an object, visuotactile integration results in an averaging effect, biasing the tactile perception toward the visual estimation (Bayesian integration)[15,16]. When estimating the weight or force of an object, visuotactile integration results in a contrast effect, biasing the tactile perception away from the visual expectation (Anti-Bayesian integration)[17,18].

The second purpose of this study was to know in which fashion, colour information is integrated with the temperature information acquired by a direct touch of an object. If it is an averaging effect, observers would tend to feel red objects warmer and blue objects cooler, and the lowest warm temperature would be lower for red than for blue in the object colour condition, and vise versa in the hand colour condition. On the other hand, if it is a contrast effect, observers would feel the reverse, and the lowest warm temperature would be higher for red than for blue in the object colour condition, and vise versa in the hand colour condition.

Results

In Experiment 1, we examined whether object colour could have an impact on the temperature judgment of the object touched by the hand. We manipulated the object colour (Figure 1b) and had participants touch the object and judge whether the object felt warm or not. The temperature of the object surface was varied adaptively based on the participants' responses to determine the lowest temperature required for the object to feel warm. Since there was no significant difference between ascending and descending staircases for both object colour ($F_{(1,11)} = 0.28$, n.s.) and hand colour ($F_{(1,10)} = 1.38$, n.s.), we pooled the data from both protocols to fit a psychometric function, and derived the "lowest warm temperature" from the temperature that corresponds to the 50% chance level. We found that the object colour (blue, eyes-closed control, red) has a significant effect on the lowest warm temperature (A repeated-measures ANOVA, $F_{(2,22)} = 5.61$, $p = .01$, partial $\eta^2 = 0.34$, see Figure 2). The lowest warm temperature for red ($M_{red} \pm SE = 32.8 \pm 0.40°C$) was larger than that for blue ($M_{blue} \pm SE = 32.2 \pm 0.46°C$) at the .05 level of significance (Post hoc Tukey Test, $q = 4.28$, $p < .05$). As a result, compared to a blue object, a red object requires a higher temperature to feel warm. In Experiment 2, we manipulated the colour of the hand (Figure 1b) and examined whether hand colour could also have an impact on the object temperature judgment. Our results confirmed that hand colour (blue, eyes-closed control, red) also had a significant effect on the lowest warm temperature (A repeated-measures
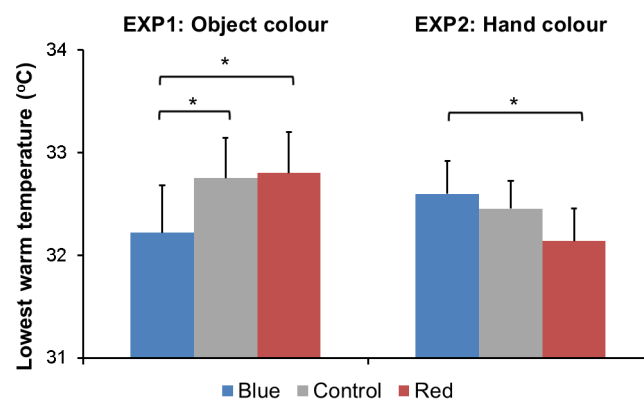

Figure 2 | Results indicating the mean ($\pm SEM$) of the lowest warm temperature. The colour manipulation in Experiments 1 and 2 is indicated by the colour of the bars, with blue, grey and red bars standing for blue colour, eyes-closed control and red colour, respectively. The number of independent data points (N) is 12 for Experiment 1 and 11 for Experiment 2 (*denotes $p < 0.05$, Post hoc Tukey Test).

ANOVA, $F_{(2,20)} = 4.58$, $p = 0.02$, partial $\eta^2 = 0.31$, see Figure 2). Interestingly, the effect of hand colour was opposite to that of object colour. It was shown that the lowest warm temperature for red ($M_{red} \pm SE = 32.1 \pm 0.31°C$) was lower than that for blue ($M_{blue} \pm SE = 32.6 \pm 0.32°C$) at the .05 level of significance (Post hoc Tukey Test, $q = 4.19$, $p < .05$), indicating that with a red hand participants tended to judge the touched object as warmer than with a blue hand.

Discussion

Here we demonstrate that not only the colour of the object (Experiment 1) but also the colour of the hand in contact with the object (Experiment 2) can have a direct impact on the temperature judgment of the object touched by hand. Our findings indicate that colour is able to have an impact on the perceived temperature even when the temperature information is acquired via direct manual exploration. Specifically, we found that a red object or a blue hand, relative to a blue object or a red hand, raises the lowest temperature required for an object to feel warm by about 0.5°C (see Figure 2), which is comparable to the effects of red and blue colour lights on perceived environmental temperature (0.4°C[9]) and on thermal pain threshold (0.3°C[19]). This change in the lowest warm temperature might seem small at first glance, but if we consider the values of the warm detection threshold (0.2°C) and the thermal discrimination threshold (0.03–0.09°C) of the hand[20,21], this change is sufficient to induce a clearly perceptible change in the perceived temperature of an object in contact. Note that we used red and blue colours in the present study because we wanted to maximize the evaluative potency of the colour information. It is expected that similar effects could be found with other apparently "warm" and "cold" colours, but probably with a smaller effect.

The effects of the object and hand colours can be explained by a hypothesis wherein the object and hand colours modulate expectations of the relative temperatures of object and hand based on the prevailing red-hot/blue-cold association (see Figure 3). The expectation of a red object being warm ($T_{obj,red}$) or a blue hand being cold ($T_{hand,blue}$) will increase the expected difference between object and hand temperatures ($\Delta T_{obj,red}$ or $\Delta T_{hand,blue}$). Given that the perceived warmness upon contact depends on the temperature difference between object and hand[14], with larger differences producing warmer sensations, people will tend to judge the touched object as less warm because the actual temperature difference would be smaller than the expected difference of a red object or a blue hand. Based on the same logic, people would tend to judge the touched object to be warmer when it is blue or when it is touched by a red hand,
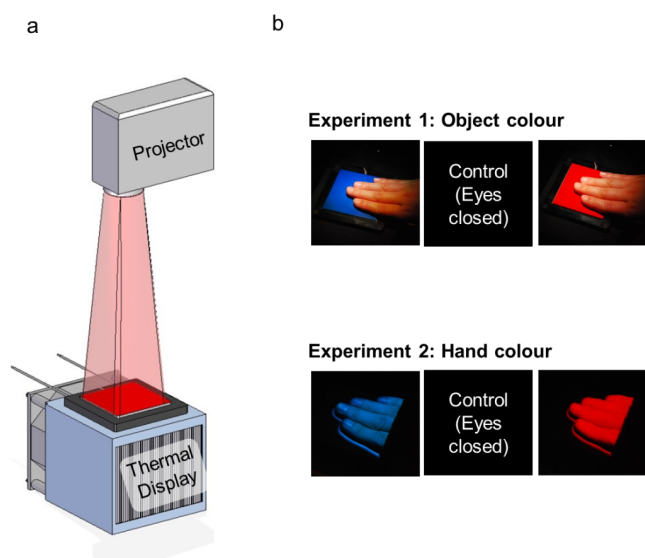

Figure 1 | Materials and methods. (a) Experimental set-up. Our system performed feedback control to the surface temperature. It could also selectively project colours onto the hand that was in contact with the surface. (b) Experimental conditions. In Experiment 1, the colour was manipulated by attaching blue or red colour paper onto the thermal display. In Experiment 2, the colour was manipulated by projecting blue or red colour onto the hand. In both experiments, an eyes-closed control condition was included.
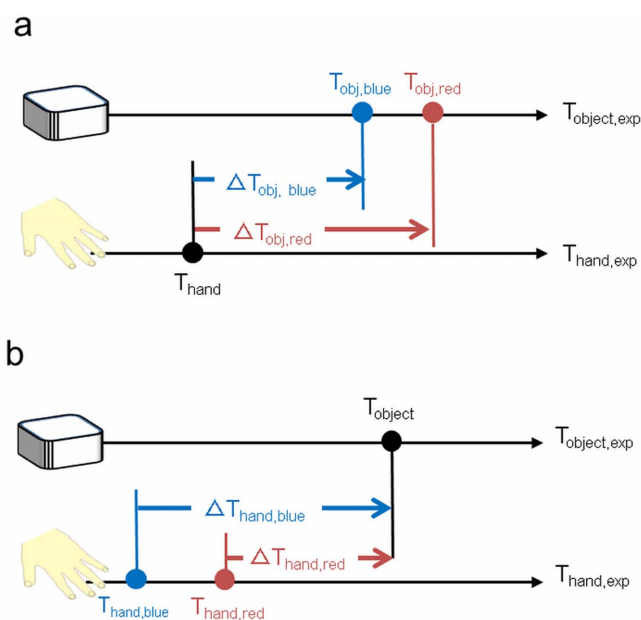
Figure 3 | Diagrams illustrating how object colours (a) and hand colours (b) modulate temperature judgments. The relative values of the expected hand ($T_{hand,exp}$) and object temperatures ($T_{obj,exp}$) before actually making contact with the object are illustrated. Our brain compares the expected temperature difference to the actual temperature difference to determine whether the object feels warm or not.

because the expected difference between object and hand temperatures ($\Delta T_{obj,blue}$ or $\Delta T_{hand,red}$) would be smaller than the actual temperature difference.

Our results indicate that a blue object is more likely to be judged to be warm than a red object of the same physical temperature, which is apparently inconsistent with the red-hot/blue-cold association. In some respects, our results are consistent with the effects of object colour reported by Mogensen and English[13], but the relationship between the two studies deserves careful consideration. In their study, participants were asked to touch two equally heated cylinders each of which were wrapped in six coloured papers and judge the warmer of the two. As the data from Mogensen and English were not analyzed statistically, we analyzed them retrospectively with a repeated measures ANOVA, and found a significant colour effect ($F_{(5,120)} = 3.83$, $p = .03$), with proportion of warmer judgments from highest to lowest was green, blue, orange, yellow, red, and purple. Among all the pairwise comparisons, green and blue were found to be significantly warmer than purple (Bonferroni correction for multiple pairwise comparisons, $p < .01$ and $p = .01$, respectively), while the difference between red and blue was not statistically significant. Their result is inconsistent with the expected order, or the reversed order, according to the conventional concepts of warm and cold colours. Mogensen and English suggested that their result might have been affected by the participants' colour preference, as purple was not considered as a pleasant colour when the study was conducted. Indeed, in a direct comparison paradigm with the temperature of two cylinders being the same, high-level cognitive influences such as preference could easily take place. In our present study, the participants only looked at one colour (either object colour or hand colour) while making temperature judgments and the object temperature changed adaptively according to staircase protocols. We expected this experimental paradigm would reveal genuine effects of colours on temperature perception reflecting the standard colour-temperature association. For further discussion of this issue, however, we have to test the effects of other colours using our paradigm.

It is known that our brain integrates visual and tactile information in estimation of a property of an object explored by the hand[15]. It has been shown that in estimating the size or the surface roughness of an object, our brain integrates expectations based on the visual information with direct sensory inputs in averaging fashion, biasing perception toward the expectations. This kind of integration is termed Bayesian integration[15,16]. Our findings suggest that instead of averaging the expected and direct temperature inputs, our brain integrates the prior expectation based on the red-hot/blue-cold association with direct temperature inputs in a way that emphasizes the "contrast" between the two. As a result, the final unified perception is opposed to the expectation. This type of integration is sometimes referred as Anti-Bayesian integration[18,22]. The colour-temperature interaction demonstrated in the present study can be regarded as a new type of contrast illusion similar to the size-weight illusion, in which a larger object is tended to be judged as lighter than a smaller object of the same mass[23–25], and the speed-force illusion, in which the perceived force from an impact on the palm is tended to be judged as weaker when the collision speed is fast compared to when the collision speed is slow[17].

While the trend of colour-temperature interaction that we demonstrated in the present study is against a general expectation from the red-hot/blue-cold association, those that have been demonstrated with temperature information acquired in an indirect, non-contact fashion are consistent with the expectation[6–8,10,11]. It is tempting to conclude that the indirect or direct way of acquiring temperature information might influence how the brain integrates colour and temperature information. However, there are several exceptions[26,27]. For example, one study showed that when participants were given warm coffee served in cups of different colours, they indicated the beverage served in a red cup tasted the warmest[26]. In this case, the temperature information was acquired directly by tasting the beverage, but the integration occurred in an averaging fashion. It is possibly due to the fact that it was the colour of the cup, rather than the colour of the target being estimated (the beverage), that was manipulated. In other words, instead of a property of the object being estimated, colour is used as an additional cue for temperature judgment in this case. Thus, the role of colour in the scenario (a property of the object itself or an additional cue) might also be a determining factor. Another possible factor could be the temporal sequence of the colour and temperature presentation. In our present study, the participants first looked at the object surface and then made contact with the object. In this sequence, the expectations of the object and hand temperatures were already formed when the direct temperature inputs were acquired by touch. In such a way, the difference between the expectations and the temperature inputs can be easily contrasted. Other contrast illusions, such as size-weight illusion and force-speed illusion, also have the similar temporal sequence for visual and tactile presentation. Taken together, it seems likely the method of acquiring temperature information (contact, non-contact), the role of colour in the scenario (a property of the object or a cue), and the temporal order of stimuli presentation influence how our brain integrates the colour and temperature information.

The effect reported in the present study is presumably based on the prevailing colour-temperature association. Such an association might emerge from the internalization of the correlations between stimuli that are present in the environment[28–31]. For example, fire and the sun are warm; hence red and yellow are the colour of warmth. Ocean and forests are cool; hence blue and green are the colour of coolness. In particular, in the case of the hand colour, the association could be linked to the fact that our skin gets redder when we are warm and blue when we are very cold. Besides the colour-temperature association derived from the cognitive or intellectual factors mentioned above, the association could also emerge from synesthesia, a neurological condition in which stimulation of one sensory or cognitive pathway leads to automatic, involuntary experiences in a second sensory or cognitive pathway[32,33].

In sum, our study provides the first experimental demonstration of colour being able to modulate temperature judgments of an object touched by the hand. The modulation effects apparently oppose the prevailing red-hot/blue-cold association. This suggests that our brain integrates prior expectations about object and hand temperatures with direct temperature inputs in a way that emphasizes unexpected information. These findings should provide a fresh insight into how our brain integrates the multisensory information when estimating an object property.

Methods

Experiment 1: object colour. *Participants.* Twelve paid participants ($M_{age} \pm SD = 26.4 \pm 6.7$ years; 7 females) participated in this experiment. They gave their informed consent before the start of the experiment. The experiment was approved by the local ethics committee and was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus. A novel system, which utilizes a thermal display and a projection unit, was developed for this study (Figure 1a). The thermal display consists of a Peltier device with a surface area of 75 mm $\times$ 75 mm, a temperature sensor and a temperature controller. The temperature controller and a PID control loop programmed in visual C++ were used to monitor and control the surface temperature of the thermal display to allow the surface temperature to be maintained within $0.2°C$ of the desired temperature. The projection unit was installed 45 cm above the thermal display and consists of a projector and an infrared (IR) camera with an IR pass filter attached to it.

The experiment was conducted in a completely dark room. The projection unit projected a white spot light with an area of 26 cm $\times$ 18.5 cm onto the object surface so that the participants could see the colour clearly in the dark room. The object colour was manipulated by attaching red and blue colour papers to the thermal display. The colours of the red and blue papers in the CIE colour space and the luminance under the spot light were (x = 0.65, y = 0.31, L = 33.3 cd/m²) and (x = 0.16, y = 0.11, L = 11.6 cd/m²), respectively.

Procedure. Experiment 1 contained three conditions (see Figure 1b), and the participants participated in all of them. In the red and blue conditions, red or blue colour papers were attached to the thermal display, respectively. In the eyes-closed condition, the participants closed their eyes throughout the experimental session.

An adaptive staircase method was used to control the surface temperature of the display. We aimed to determine the lowest warm temperature required for the surface to be judged as warm. Each condition was blocked in one single staircase. The skin temperature of participants' right hand was maintained with a hot plate kept at $33°C$ for 5 minutes at the beginning of each staircase. After the initial adaptation, they were asked to place their chin onto the chinrest and close their eyes. The initial temperature of the thermal display was selected randomly from 20 to $24°C$ for an ascending staircase and 36 to $40°C$ for a descending staircase. Upon hearing a sound cue, the participants moved their right hand from the hot plate to the thermal display, which was placed 30 cm leftward to the hot plate. A plastic stopper was installed in front of the display to guide the participants to stop their right hand 2 cm above the display. Three seconds after the sound cue, a second sound cue was presented and the participants were instructed to open their eyes to look at the object surface (They kept closing their eyes throughout the staircase for eyes-closed condition). Three seconds later, the third sound cue was presented and they were instructed to touch the surface for 1 s. At the end of the contact, a forth sound cue was presented to prompt the participants to withdraw their hand from the display and report verbally whether the object surface felt warm or not ("yes" or "no"). After they gave their answer, they closed their eyes and moved their hand back to the hot plate to wait for the start of the next trial. The interval between trials was 10 s.

The surface temperature of the next trial was determined based on participants' responses. It decreased when a participant responded "yes" (the surface felt warm) and increased when they responded "no." The initial step size for temperature change was $3°C$, and after the first reverse point, the step size was decreased to $2°C$. The step size was set at 1 and $0.5°C$, respectively after the second and third reversal points. To prevent the participants from predicting the sequence of the staircase stimuli, we randomly chose 4 trials between the 8th and 19th trial and presented "surprising" stimuli that were not related to the staircase in those 4 trials. Each staircase ended when 20 trials had been performed. The temperature of the stimuli presented in the staircase had an upper limit of $45°C$ to avoid painful sensation and skin damage.

For each condition (blue, eyes-closed, red), four staircases (two ascending and two descending staircases) were conducted to give a total of 12 staircases. The 12 staircases were divided into six experimental sessions and presented in a randomized order. Each session lasted for approximately 30 min.

Analysis. For each participant in each condition (e.g. object colour-red), we conducted four staircases (two ascending and two descending staircases) and recorded the thermal display temperature of each trial in those four staircases. We used all data points (i.e. the thermal display temperature) gathered in these four staircases to fit a psychometric function and derived the "lowest warm temperature" for the participant in that specific condition. The lowest warm temperature is defined as the temperature that corresponds to the 50% chance level. The effect of colour on "lowest warm temperature" was analyzed with a repeated-measures ANOVA, with colour (blue, eyes-closed control, red) as the within-participant factor. Tukey Test was used for post-hoc comparisons. Significant level in all statistical tests is 0.05.

Experiment 2: hand colour. *Participants.* Eleven participants ($M_{age} \pm SD = 25.3 \pm 5$ years; 5 females) participated in this experiment. Three of them also participated in Experiment 1. They gave their informed consent before the start of the experiment. The experiment was approved by the local ethics committee and was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus. The same thermal display and projection unit were used here. We manipulated the hand colour by projecting red or blue colour onto the hand region selectively during contact (see Figure 1b). The hand region was extracted using an infrared (IR) camera and IR LEDs placed next to it, which are used to illuminate IR lights to the projection area. Because the IR reflectance of the human skin and the surface of the thermal display are considerably different, the hand region can be robustly extracted from the other region in a captured IR image. We then filled the extracted hand region with uniform red or blue colour and the other region with uniform black to make a projection image. The final red and blue colours appeared on the hand in the CIE colour space and the luminance are (x = 0.68, y = 0.31, L = 37.9 cd/m²) and (x = 0.14, y = 0.07, L = 3.8 cd/m²), respectively.

Procedure. The procedure here paralleled that in Experiment 1, except that in this case the colour of the hand was manipulated.

Analysis. The analysis here paralleled that in Experiment 1.

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Author contributions

Additional information

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