IN SEARCH OF EVIDENCE FOR THE HUE-HEAT HYPOTHESIS AND ITS POSSIBLE ENERGY- AND COST-EFFECTIVE APPLICATION IN THE AIRCRAFT CABIN

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Nowadays the realization of coloured light scenarios in aircraft cabins is easily accomplished by using LED-technology. The central question of this contribution is whether the use of coloured light can influence passengers' temperature sensation and make the climate be perceived cooler or warmer.
Experiments conducted in the context of our research project (LiKab[1)]) in a light laboratory (designed as a mock-up aircraft cabin) suggest the possibility of such an influence [1]. The results are in line with psychological research on the so called "hue-heat hypothesis" [2] which states that the temperature in environments with warm colours (or illuminated respectively) is perceived warmer and that of environments with cold colours (or illuminated respectively) is perceived cooler.
Based on the promising results obtained in the laboratory, altogether four experiments were conducted under more realistic conditions. Design and results of these experiments in the test carrier, a cabin of a single-aisle aircraft with 70 seats (Dornier 728), are reported. A total number of *N*=199 subjects participated in the study.
Two lighting scenarios, a warm hue of yellow and a cool hue of blue, were combined with various temperatures in different experimental sessions in the aircraft cabin, whereas air draught and humidity were kept constant. Participants worked on computerized questionnaires to document their climate perceptions and evaluations.
The results show an effect in the hypothesized direction. It is shown that the impact of lighting colour on climate perception and evaluation can be observed in the whole sample and in certain subgroups of subjects. Although the effect seems to be rather small, it is in correspondence to former studies [3]. A large-scale application of this effect in the aircraft/aviation industry could lead to sustained energy savings and thus contribute to energy and cost effectiveness.

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1. INTRODUCTION

A considerable amount of research in the fields of experimental psychology, applied psychology and psychological ergonomics has been done about the possible influence of colours or coloured surfaces on thermal sensation and thermal comfort. This research, which may be referred to as testing the 'hue-heat-hypothesis', mainly took place between the 1960s and late 1980s (see [2] for a comprehensive review). The 'hue-heat hypothesis' claims that a cool ambient colour leads to a cooler temperature perception and that a warm ambient colour leads to a warmer temperature perception. The basic aim from the beginning was the possible contribution to energy saving by applying a possible effect in industrial and every day appliances. Energy saving and energy-efficiency is nowadays a widespread motivation for doing research, because of the importance of environmental impacts, protection of energy resources and cost control in virtual every industry, especially in the energy-hungry aviation business [4, 5].
The results of the mentioned research on the thermal effects of colours in the 20th century were quite disappointing from the researchers' point of view: Either no effects of colour on temperature perception were found [6, 7] or observed effects were very small and at that time of no practical significance [3]. Fanger et al. [3] showed for example a difference in temperature sensations of 0.4°C depending on the illumination of a room in either blue or red light.
Some aspects, besides the methodological criticism, which might justify new experiments in this field on its own (e.g. use of very small sample sizes, cf. [2]), made it for us worthwhile to conduct new studies in the field of applied psychology according to the 'hue-heat hypothesis': First, and above all, a lot of energy is consumed

in the aviation industry and energy costs are a very important cost-factor for airlines, a fact that also leads to a more sophisticated design of energy-efficient engines. For example, fuel consumption of turbojet engines has been reduced by approximately 50% since the 1950s [8, 9]. If an impact of lighting on temperature and comfort sensation can be found, even a small effect - systematically applied - could have a measurable impact on energy consumption and costs. Second, if an effect of ambient colour on thermal comfort exists it could easily be induced because nowadays aircraft are (or can be) equipped with modern and potential LED lighting systems, which allow the establishment of various lighting situations. Third, preliminary research of our group shows that one could be quite optimistic of the validity of the' hue-heat-hypothesis' in applied cabin environments [1]. Finally, we are also very interested in maintaining and even raising the level of the perceived comfort: We think that a proper climatization and certain ambient lighting situations, established by state of the art LED techniques, can enhance the passengers' comfort in the aircraft cabin.

Of course, our research was also theoretically driven. To define comfort we used an approach which is in accordance with the relevant psychological and ergonomic literature. The passengers' comfort is a function of subjective well-being [10] which is influenced by multiple objective environmental factors [11, 12]. According to the specific situation in an aircraft cabin our research group formulated a comfort model which includes a variety of objective factors (temperature, air-draught, humidity etc.) with their effects on passengers' subjective thermal comfort. This model and details have been published in Winzen et al. [1] and Marggraf-Micheel, Winzen & Albers [13]. From a more theoretical perspective, the testing of the 'hue-heat hypothesis' means to examine if the objective factor lighting, with direct or indirect influence on perceived comfort, has to be considered in models of passengers' thermal comfort.

These practical and theoretical aspects taken together led to the idea to test the 'hue-heat-hypothesis' in a realistic aviation environment, a cabin mock-up of a single-aisle aircraft, with a reasonably large sample of subjects. We wanted to test the influence of coloured ambient lighting on passengers' thermal perceptions and their well-being and thus thermal comfort. If there is a positive outcome this could have interesting theoretical and practical implications: Coloured light could be used in energy- and cost-saving applications in the aviation industry and on the other hand this would mean that the lighting situation is an environmental factor which has to be considered in passengers' (thermal) comfort models.

2. METHOD

2.1 Participants

The experiments conducted for this study involved a sample of altogether N=199 subjects with normal colour vision. In each experimental session n=50 subjects took part (session one comprised n=49 due to organizational reasons). The mean age in the whole sample was M=32.6 years (SD=10.8), the age range was between 18 and 55. The sex ratio was 50:50 in the whole sample as well as in each of the four experimental sessions. A prerequisite for the participation in the study was a school graduation qualifying to study at a German university (German 'Abitur'). Subjects were recruited by a market research institute and were paid 60€ each for their participation.

2.2 Instruments

2.2.1 Cabin mock-up

All experiments were conducted in the single-aisle aircraft mock-up Do728, which is located at the DLR Institute of Aerodynamics and Flow Technology in Göttingen (Germany, see FIGURE 1).

FIGURE 1: Mock-up Do728 ©DLR

This aircraft is a single aisle jet with a complete cabin interior comprising 70 seats in 14 rows, two seats on the right and three on the left side of the cabin. 50 seats were used for subjects, 4 rows were occupied with thermo-dummies equipped with sensors that measure different climate parameters at different locations. The air conditioning system of the mock-up is fully operative and provides mixed air through 64 inlets which are arranged in two lines along the ceiling and below the overhead bins. After circulation the air leaves the cabin through 24 air outlets located at the cabin floor. The cabin and climate situation can be seen as very realistic and generic for a single-aisle aircraft of comparable size. Only the pressure inside the mock up cannot be varied and equals ground conditions.

2.2.2 Climate parameters and climate situations

For our experiments we wanted to establish different temperatures as independent variables. We aimed at implementing two different temperatures per experimental session which were to be paired with two different lighting situations (cf. 2.2.3).
Other climate parameters, which might have strong effects on thermal comfort, were intended to be kept constant. The air draught was kept steady at values of 0.14 to 0.16 m/s and thus far below 0.3 m/s, a comfort-critical value [14]. The humidity was kept as constant as possible at values below 30% to establish conditions resembling the situation in real flights.
The range of temperatures used is also within the comfort-critical range given by CEN [14].
Unfortunately, two operationalizations of climate scenarios could not be used. TABLE 1 shows the temperatures of the six established climate situations which could be used for further analyses and the respective sessions. The temperature values are averaged from all temperature measurement devices inside the mock-up.

TABLE 1: Temperatures of climate situations used for data analysis

Temperature [°C]	21.5	22.5	23.1	23.6	24.3	25.4
Experimental session No.	3	3	4	4	1	2

2.2.3 Lighting situations

The cabin was illuminated by a high power LED-lighting system with two strips fixed on either side of the aisle at the overhead bins near the ceiling. Two further strips were fixed on the side panels above the windows, as in real aircraft (cf. FIGURE 2 & FIGURE 3).
All given lighting specifications are measurements of a spectroradiometer (specbos 1211, spectral range 350–1000 nm).
TABLE 2 shows the specifications of the blue and yellow lighting situations. FIGURE 2 and FIGURE 3 show the experimental situation for phases of blue and yellow. The specifications of the lighting situations were not changed between experimental sessions and were always the same.

TABLE 2: Description lighting situations

Lighting	Centroid wavelength [nm]	Illumination (at ceiling) [lux]
Blue	495.9	232.1
Yellow	608.0	177.0
Neutral	520.4	290.9
Green	526.2	200.3
Violet	517.5	169.9

In breaks and for short neutralization phases, a neutral lighting was used. Furthermore a hue of green and one of violet were used to have a broader set of coloured lighting situations that were evaluated by the subjects (all specifications can be seen in TABLE 2). The intention was to minimize the likelihood of hypothesis guessing and according behaviours.

FIGURE 2: Experimental situation in cabin mock-up: blue lighting situation ©DLR

FIGURE 3: Experimental situation in cabin mock-up: yellow lighting situation ©DLR

2.2.4 Questionnaires

Several variables were measured using questionnaires that were administered on pocket PCs (HP iPAQ214, 400 TFT touch screen display, input by stylus pen).
First, subjects were asked for demographical data. In the repeated parts for the climate/ lighting scenarios, subjects were asked about the effects of the lighting situation including questions about the colour of light, the temperature appearance of the light, its brightness etc. Furthermore, they were asked about their perception and evaluation of the climate in the aircraft cabin (temperature, air draught, humidity etc.). Generally, it was asked first about a parameter's intensity (e.g. "How intense is the colour's brightness?") on a seven point rating scale. Then the question followed, to which extent this intensity induces comfort (e.g. "How comfortable is the colour's brightness?") which had to be answered on a five point rating scale.
Subjects were also asked to give an estimation of the temperature in degrees Celsius.
Different aspects of psychological and physiological well-being were recorded as well [15, 16 for details cf. 1].
Additionally, participants had to answer questions about more stable preferences and personality traits. Participants had to classify themselves in different groups regarding climate preferences: sensitivity for coldness (high vs. low), sensitivity for heat (high vs. low), sensitivity for air draught (high vs. low), sensitivity for air quality (high sensitivity for used/stuffy air vs. low sensitivity) and sensitivity for dry air (high vs. low).
Finally, the so called big five personality traits (i.e. Openness to experience, Conscientiousness, Extraversion, Agreeableness and Neuroticism) were assessed once by a well-established test called BFI-K [17].
The whole package of questionnaires is already well-evaluated (e.g. [18]) and details according to the scales and their measurement reliability can be found in Winzen et al. [1].

2.3 Design and procedure

For the data collection in the four experimental sessions, two different climate scenarios were paired with two different lighting scenarios in each session. Whereas the lighting scenarios were the same (blue and yellow) in all experiments, the climate scenarios were different between the sessions to increase the number of obtained data points for climate scenarios (here: temperatures). The two independent variables (climate situation x lighting situation) established a two-factorial design. For analyses further inter-person factors were used (see results section).
Participants were instructed to wear standardized clothes (long arms and legs, shoes not covering ankles etc.).
The course of events was the same for all four experiments:
The participants boarded the mock-up and sat down on assigned seats. The assignment of seats took care of an alternation of male and female subjects within every experiment.
Once seated, subjects received a briefing about emergency situations, the handling of the pocket PCs and a rough overview of the course of events.
Basically, the procedure in all four experiments was the same, only the sequence of lighting colours and the temperature scenarios were changed between sessions. The procedure can be seen in FIGURE 4
The sequence started with a forerun that was needed to establish the first climate scenario. Within this forerun there was a lighting situation acting as a red herring regarding the background of the experiment (i.e. green or violet), after ten minutes of this illumination participants worked on the light/ climate questionnaires.

Stabilization of climate 1		Climate/ temperature 1		Change of temperature to climate 2		Climate/ temperature 2	
neutral lighting	green	yellow	blue	neutral	violet	blue	yellow

FIGURE 4: Exemplary overview of experimental procedure

Following the forerun, the experimental lighting phases were realized for ten minutes respectively, and then participants had to work on the questionnaires for approximately ten minutes under consistent conditions. After one yellow and one blue lighting situation the climate was changed, during this time the participants had a break with snacks, worked on the personality questions and were exposed to another irrelevant lighting scenario (violet or green).
The sequence of light scenarios and of temperatures (i.e. warmer climate first vs. cooler climate first) was balanced between the experimental sessions.
During times of mere exposure to a lighting situation or during waiting periods, subjects were entertained by audio-visual material via the cabin entertainment system. All changes of cabin lighting took place after a phase with neutral light for one minute.
One experiment lasted for approximately three hours of net time in the cabin for the participants.
With this procedure we established four phases for obtaining dependent variables from the questionnaires under the influence of the independent variables (climate (cf. TABLE 1) and lighting situation (blue vs. yellow)).

3. RESULTS

Before starting the analyses we examined the data with regard to integrity. We had to exclude the data of three participants from the analyses because they showed consistent patterns of answers that revealed that these subjects either did not take the questionnaires seriously or were not able to work on the questionnaires.
Analysis of the fundamental five personality factors showed that the means of the five factors did not differ between the four experiments, thus it was justified to combine the subjects' data (cf. TABLE 1) for further analyses.
Results will be reported with regard to the most important dependent variables: the perception of temperature (1: "very cold" to 7: "hot"), the evaluation of the degree to which this is comfortable (1: "very unpleasant" to 5: "very pleasant"), the subjects' estimation of temperature (in degree Celsius) and the overall contentment with the climate situation (1: "very dissatisfied" to 5: "very satisfied").
First we studied the effects on the whole sample and then we analyzed different subgroups.

3.1 Results for the whole sample

FIGURE 5 to FIGURE 8 show the mean values of the four dependent variables over the climate situations (abscissae) and lighting situations (different lines). The results of the analyses of variance (ANOVAs) can be seen in TABLE 3.
The results indicate that all means differed significantly. This means that the climate was perceived warmer and that the temperature felt more comfortable in yellow lighting. Also, on average the temperature estimation in degrees Celsius was higher and the overall contentment with the climate was higher when the cabin was illuminated in yellow.
A look at the figures shows that the effects were especially prevalent in the lower and mid-high temperatures of our used spectrum. However, the sizes of these effects are small if one uses an established classification of effect sizes [19], which states that values below ε=.2 are small.

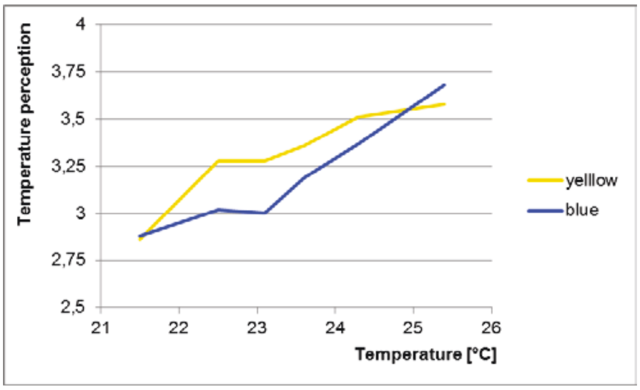

FIGURE 5: Temperature perception as a function of climate (temperature) under yellow and blue lighting conditions

TABLE 3: Descriptive statistics for different variables of evaluation in blue and yellow light and test-results of ANOVAs and effect sizes

	Yellow *M (SD)*	Blue *M (SD)*	*df*	*F*	*p*	Effect size (*ε*)
Temperature Perception [1-7]	3.31 (1.1)	3.19 (1.1)	1	10.6	.001	.14
Temperature evaluation [1-5]	2.88 (1.1)	2.76 (1.0)	1	10.2	.001	.13
Temperature estimation [°C]	19.24 (2.4)	19.05 (2.5)	1	8.0	.005	.12
Contentment with climate situation [1-5]	3.19 (0.9)	3.06 (0.9)	1	10.1	.002	.13

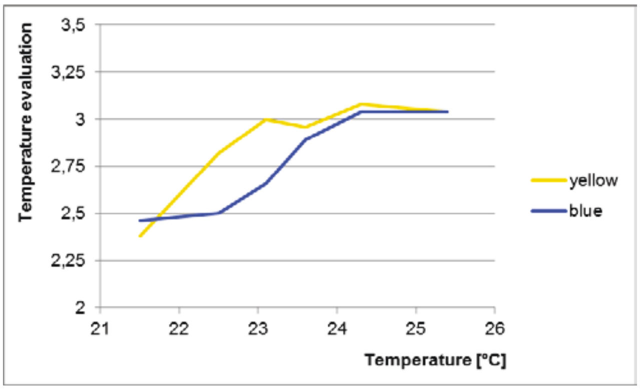

FIGURE 6: Temperature evaluation as a function of climate (temperature) under yellow and blue lighting conditions

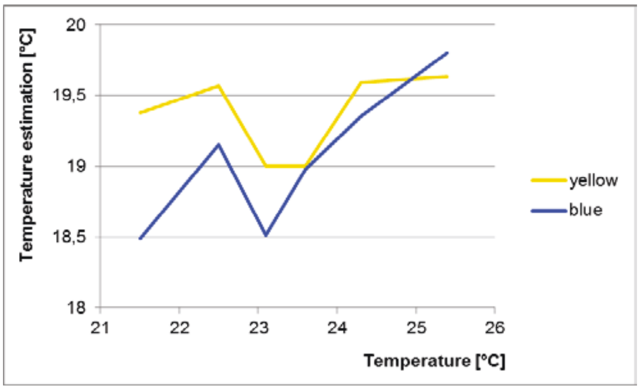

FIGURE 7: Temperature estimation in degrees Celsius as a function of climate (temperature) under yellow and blue lighting conditions

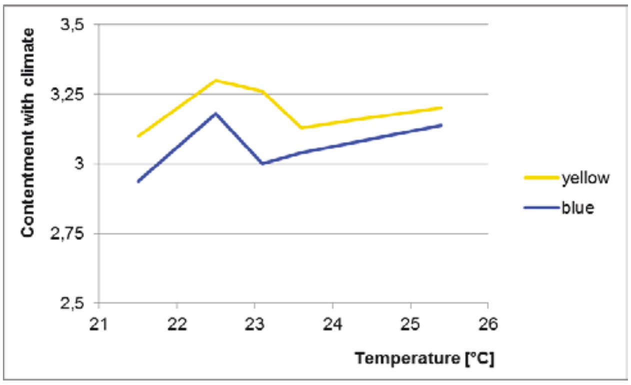

FIGURE 8: Contentment with climate as a function of climate (temperature) under yellow and blue lighting conditions

3.2 Results for subgroups

To further evaluate the observed effects and to get more knowledge about where the effects might stem from, we analyzed the effects of the two different lighting situations in various subgroups.

Sex

The whole sample was divided in two equally large sex-subgroups.

In the women-subgroup effects of yellow lighting could be observed: the temperature was perceived as higher ($F_{(1)}$=9.78, p<.05; $ε$=.18) and this was evaluated as being more comfortable ($F_{(1)}$=6.23, p<.05; $ε$=.15;) and the overall contentment with the climate was higher in yellow lighting ($F_{(1)}$=4.47, p<.05; $ε$=.15).

In the male subgroup also three means differed significantly, again with higher means in the yellow lighting situation: the temperature was evaluated more positively ($F_{(1)}$=4.10, p<.05; $ε$=.12), the estimated value in degree Celsius was higher ($F_{(1)}$=4.71, p<.05; $ε$=.13) and also the male participants felt more content with the climate situation ($F_{(1)}$=5.64, p<.05; $ε$=.14).

Again, we found a pattern in favour of yellow lighting situations but with quite small effect sizes.

Sensitivity for coldness

The sample was further divided by the sensitivity for coldness. There were those who were sensitive for coldness (=high coldness sensitivity) and who were not (=low coldness sensitivity). In our sample a majority of 64% classified themselves as sensitive to coldness.

For the participants with low sensitivity for coldness no significant effects between the blue and yellow lighting situations could be found. The high-sensitive group felt more content with the climate situation in yellow light ($F_{(1)}$=6.50, p<.05; $ε$=.17).

Sensitivity for heat

Also, the sample was divided by the sensitivity for heat (high heat sensitivity vs. low heat sensitivity). Almost half of the subjects in our sample were highly sensitive in this regard (48.5%). These subjects did not show any significant differences at all. Those who were low sensitive for heat showed no significant result for the temperature estimation and two nearly significant mean differences for temperature perception and evaluation (p=.06 and p=.08, respectively). One significant mean difference was found in this subgroup: these participants were more content with the climate situation in yellow lighting ($F_{(1)}$=5.64, p<.05; ε=.17).

Sensitivity for air draught

The last division into subgroups was performed by the sensitivity for air draught, which was either high or low. The majority of 59.3% classified themselves as sensitive for air draught.
In contrast to the effects reported before the low-sensitive minority had a tendency of perceiving the temperature as higher when the cabin was illuminated in *blue* (p=.05). And these participants estimated the temperature as being higher in blue light ($F_{(1)}$=9.14, p<.05; ε=.23).
The high-sensitive subgroup showed effects in the expected direction, i.e. higher means in yellow cabin light. The perceived temperature was higher ($F_{(1)}$=10.30, p<.05; ε=.22) as well as the estimation of the temperature ($F_{(1)}$=6.23, p<.05; ε=.21) and the high sensitive subjects felt more content with the climate in yellow light ($F_{(1)}$=4.47, p<.05; ε=.17).

4. DISCUSSION

The aim of this study was to analyze the influence of coloured light in an aircraft cabin on the thermal sensations and evaluations of passengers. In a pre-study in a laboratory a thermal effect of coloured light had been confirmed [1, 13], and the results of this study in a more realistic environment are positive, too.
Especially in a certain corridor of temperatures (in the area of roughly 22°C to 24.5°C) a main effect of the lighting situation can be observed. The values in this corridor can be seen as typical temperatures one can expect for the climatization in real aircraft. Therefore our results should have relevance for the aviation industry. Subjects tend to have slightly warmer thermal sensations in yellow light and slightly colder sensations in blue light. This comes along with a slightly higher satisfaction with the (whole) climate situation in yellow light.
To get a deeper insight into the factors that might moderate the effects, we had a look at different subgroups. Sex does obviously not play a major role for the susceptibility for the ‘hue-heat’ effect, the results of male and female subjects were comparable. The sensitivity for coldness is a factor, although with minor importance, that seems to moderate the susceptibility for thermal effects whereas only sensitive people in this regard felt more comfortable with the climate in yellow lighting.
The sensitivity for heat is a factor that influences the thermal effects of lighting also mildly. Here, low sensitive subjects tend to show the effects in the direction of the ‘hue-heat-hypothesis’ and they feel more comfortable in yellow lighting.
The sensitivity for air draught plays a bigger role, although not all the mean differences are significant. In these subgroups we observed the most interesting differences in means and in patterns for those who are low sensitive (they reacted in a non-expected fashion, in favour of blue lighting) and those who are sensitive for air draught. These sensitive subjects show (again small) effects in the direction the ‘hue-heat-hypothesis’ postulates. When one considers that these subjects were in the majority of our representative sample, then you have to expect a substantial amount of people who might be influenced by the lighting situation with regard to perception and evaluation of the climate in the cabin of a real airline aircraft.
What do these results mean? We have shown that the ‘hue-heat-hypothesis’ can be corroborated in realistic cabin environments especially for sensitive subgroups, mainly for air draught. The more favourable lighting colour to use seems to be yellow because it contributes, directly or indirectly by means of a kind of ‘psychological’ warming-up, to the overall contentment and satisfaction with the climate.
The rather small impact the coloured lighting has on thermal sensation is well in accordance with earlier studies. For example, Fanger et al. [3] showed a colour effect on temperature sensation of 0.4°C. Our results also hint at stable thermal effects that are rather small.
Does this all mean that our results are of no practical significance, like Fanger et al. [3] con-

cluded? We think no. As stated initially, today energy saving is a topic in industry that is more important than ever before. So we think that even small effects have the potential to lead to vast energy-savings: The saving of kerosene for one aircraft by being able to alter the cabin temperature of the air condition to a value only slightly different may be quite small. However, this effect cumulated over many aircraft (from one airline or even manufacturer) may lead to enormous savings of energy and thus money. We think it is especially worthwhile to think about an application as coloured light could be implemented easily all the more in aircraft of the upcoming generation.
Finally, our findings indicate that the colour of lighting is an objective factor that has an influence on subjective well-being, especially for susceptible persons. Future models of thermal comfort should integrate this objective factor.
Further studies might help to generate more precise ideas about the nature and extent of these effects and the intra- and extra-personal circumstances that facilitate or promote them. Also, it may be interesting to know if there was another pattern of results if our studies were repeated in a pressurized aircraft in real flight. Finally, on the more technical side, experiments or theoretical computations should clarify how much energy and costs are saved in applying the 'hue-heat' effect in certain industrial environments, like in large or small airlines and by aircraft manufacturers.

Acknowledgement

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