



# Artificial skylight effects in a windowless office environment



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## ABSTRACT

Research on the effects of windows has clearly indicated that humans want and need daylight to perform and feel well in indoor environments. However, until now, beneficial skylight effects have rarely been investigated. The present laboratory study aimed to quantify temporary artificial skylight effects using a randomized controlled study design.

One hundred healthy young subjects either stayed in a windowless office environment that was illuminated by fluorescent lamps or an artificial skylight system that provided a virtual view of a cloudless sky and sun. Subjects rated room atmosphere parameters and their mood states, and participated in two different decision-making tests.

Our results indicated that study participants felt more connected to the nature and perceived the windowless test room as more “lively,” and less “tense” and “detached” under artificial skylight as compared to that under fluorescent illumination. Furthermore, under artificial skylight, subjects reported lower feelings of tension, anxiety, and claustrophobic symptoms, and a higher positive mood state. Finally, subjects made riskier as well as more selfish decisions under artificial skylight.

Thus, daylight-substituting technologies may profoundly influence mood states and alter decision-making behavior in windowless environments.

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## 1. Introduction

In 2012, artificial lighting accounted for 17% of the electricity used in US commercial buildings [1] and consumed more power than refrigeration, ventilation, or cooling. It is estimated that the utilization of daylight can reduce the energy consumption on lighting by up to 77% [2]. Daylight predominantly enters buildings via windows, and, to a small extent, via skylights (a mere 3% of American one-floor commercial buildings' floor areas have integrated skylights [3]).

The first systematic review [4] of how people react to windows and windowless environments was motivated by energy conservation considerations in the early 1970s. At that time, building design was stimulated by technological advances (e.g., in artificial lighting), and the idea that the energy consumption of buildings could substantially be limited by reducing window sizes or even

eliminating windows. This review unequivocally demonstrated that windows have important psychological functions for humans (e.g., providing a view to the outside and mitigating feelings of tension, isolation, and monotony) and further reviews underlined the beneficial effects of daylight on work-related parameters and well-being, especially in schools, hospitals, and workplaces [5–7]. Today, there is convincing evidence that daylight exposure reduces stress and negative affect [8], enhances mood and executive functions [9], and, in the long run, improves physical and mental health [10] in people staying indoors.

This knowledge is reflected in current lighting standards (e.g., the German Industrial Standard DIN 5034-1 “daylight in interiors—Part 1”) that unanimously recommend that rooms should be illuminated by daylight and provide a direct view to a landscape. Recently, additional design metrics focusing on non-visual daylight effects [11–13] have been proposed.

In contrast, research on the beneficial effects of skylight is scarce. Until now, to our knowledge, only two studies have documented favorable effects of diffused skylights (without directly seeing the sky). In one study [14], it was shown that standardized

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math and reading test scores of second-to fifth-grade students significantly increased in three US school districts. In another study [15], an increase in sales (up to 6%) in Californian stores was reported. The authors of both studies discussed higher illumination levels under skylight compared to artificial light as a main reason for reported learning and sales effects.

Indoor environments, however, sometimes lack daylight openings due to constructional, safety, or hygiene reasons. For these environments, the integration of daylight substituting artificial lighting technologies is considered to reduce feelings of monotony, isolation, and entrapment. Today, several prototypes of virtual windows and skylights exist [16–18]. However, research on the beneficial effects of these technologies has not revealed clear results [18–22].

In the current study, we used an artificial skylight technology, which imitated the Rayleigh scattering process of light passing through the atmosphere (i.e., diffusing the short-wavelength portion of light) by utilizing a nanostructured material coated on acrylic glazing. This artificial skylight simulated a ceiling opening and created a virtual outlook to a cloudless sky and sun. A previous study [23] conducted by our research group demonstrated that this technology generates a natural room atmosphere, and the artificial sun illuminating a restricted area of the windowless environment induced a strong feeling of being in contact with the nature.

There exists a growing body of evidence to suggest that exposure to sunlight increases positive mood and decreases negative mood (e.g., [24–27]). Some studies even have documented effects on financial decision-making behavior, e.g., sunlight exposure was significantly correlated with higher stock market index returns [28] and higher risk tolerance in lotteries [29].

Furthermore, studies have reported that exposure to sunlight affected social behavior, e.g., increased the willingness to assist an interviewer [24], tip amounts [24,30], and the probability to offer spontaneous help [31], and enhanced philandering [32].

Therefore, we hypothesized that artificial skylight and sunlight exposure may deploy direct beneficial effects on mood states, increase risk tolerance/decrease risk aversion in decision-making behavior, and trigger social behavior in an indoor environment.

## 2. Material and methods

The test setup comprised two adjacent windowless rooms of equal volume ( $3\text{ m} \times 4\text{ m} \times 2.4\text{ m}$ ) and achromatic room surfaces and furniture. Each testing room was equipped with two computer workstations.

### 2.1. Room light interventions

In one test room (called “conventional illumination” henceforth), three louver luminaires with fluorescent lamps were

installed (Fig. 1, left picture). In the second test room (called “skylight illumination” henceforth), an artificial skylight with an area of  $80\text{ cm} \times 195\text{ cm}$  (13% of the floor area) was integrated into the ceiling (Fig. 1, right picture).

The installed artificial skylight mimicked a daylight opening on a cloudless sky and an artificial sun (Fig. 1, right picture). The artificial sun was kept in a stable position ( $60^\circ$  elevation angle) and thus generated a constant light condition in terms of the light spectrum, light intensity, and light distribution. Luminance levels of the artificial sky and sun were significantly lower compared to their natural counterparts (artificial sky:  $709\text{--}1179\text{ cd/m}^2$ ; artificial sun:  $1\text{--}2\text{ Mio.cd/m}^2$ ). Furthermore, the artificial sun did not emit infrared radiation, which would have caused a heat sensation on the subject's skin. Although study participants were exposed to a minimal dose of UV-A radiation under the artificial skylight, perceived UV-dose was negligible compared to that of natural sunlight exposure.

In contrast, the artificial skylight imitated a real skylight by providing the following visual features: (1) the solid angle of the artificial sun was the same as that of the real sun, (2) subjects perceived a parallax phenomenon when they directly gazed at the sun under different viewing positions, (3) the artificial sky showed 3D-depth, (4) objects illuminated with the artificial sun generated penumbra and blue-toned shadows, and (5) the brightness ratio of sunlit to shaded areas in the test environment was comparable to the brightness ratio outdoors.

To generate similar indoor illumination scenarios for the subjects while performing tests, the seating position and location of the computer screen were carefully chosen to avoid any visual impairment (Fig. 2, left picture). Consequently, subjects were not exposed to direct artificial sunlight while performing test on the computer screen and filling out the questionnaires and the photometrical conditions under both lighting scenarios (see Table 1, Column 1 and 2) were comparable.

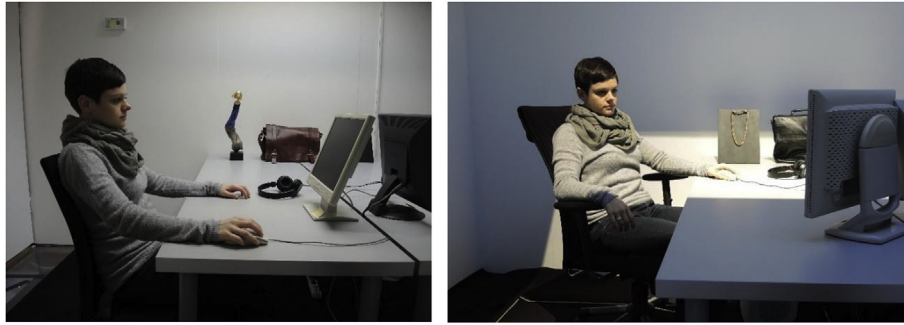
In contrast, the photometrical measures under skylight illumination (see Table 1, Column 3) were distinctly different during the resting periods because subjects were instructed to change the seating position to experience direct artificial sunlight exposure (see Fig. 2, right picture). Under conventional illumination, photometrical measures were identical while performing tests and during resting periods.

A photobiological risk assessment, in accordance with current standards (i.e., CIE S 009/E:2002 Photobiological Safety of Lamps and Lamp Systems), was carried out for the artificial skylight system. We could reveal no risks (e.g., regarding blue-light, actinic ultraviolet, near-ultraviolet, retinal thermal, and infrared hazards), especially when subjects rested and were exposed to direct artificial sunlight.

The spectral, intensity-related, and photopigment-related photometrical measures of the two lighting conditions have been



Fig. 1. Fisheye's perspectives of the two test environments with conventional [left] and skylight illumination [right].



**Fig. 2.** Left: A subject conducting a performance test under conventional illumination; Right: A subject recovering under skylight illumination (both photos have been reproduced with the permission of the subject).

**Table 1**

Photometrical measures under conventional illumination and skylight illumination while working (filling out questionnaires and performing tests on the PC) and resting (relaxed seating position with eyes open). Under conventional illumination, photometrical measures did not differ significantly while working and resting. \*Glare while working was measured with different metrics for the two lighting conditions, unified glare rating (UGR; according to DIN EN 12464-1) for conventional illumination and daylight glare probability rating (DGP [33]) for skylight illumination. \*\*Photopigment-related measures were derived following the recommendations of Lucas et al. [34].

|                                                             | conventional illumination | skylight illumination (working) | skylight illumination (resting) |
|-------------------------------------------------------------|---------------------------|---------------------------------|---------------------------------|
| <b>light spectrum - related measures</b>                    |                           |                                 |                                 |
| CIE 1931 chromaticity coordinates (x; y)                    | (0.357; 0.370)            | (0.347; 0.352)                  | (0.336; 0.356)                  |
| correlated color temperature (Kelvin)                       | 4661                      | 4970                            | 5362                            |
| color rendering index (Ra)                                  | 89                        | 88                              | 87                              |
| <b>visual performance - related measures</b>                |                           |                                 |                                 |
| glare rating while working *                                | 14                        | 0.24                            |                                 |
| minimal luminance within field of view (cd/m <sup>2</sup> ) | 26                        | 19                              |                                 |
| maximal luminance within field of view (cd/m <sup>2</sup> ) | 136                       | 249                             |                                 |
| mean horizontal illuminance (lux)                           | 462                       | 516                             |                                 |
| uniformity at desk level (g <sub>1</sub> )                  | 0.87                      | 0.21                            |                                 |
| <b>corneal intensity - related measures</b>                 |                           |                                 |                                 |
| illuminance (lux)                                           | 329                       | 334                             | 852                             |
| irradiance (μW/cm <sup>2</sup> )                            | 101.18                    | 122.47                          | 315.46                          |
| photon flux (1/cm <sup>2</sup> /s)                          | 2.79 * 10 <sup>14</sup>   | 3.40 * 10 <sup>14</sup>         | 8.75 * 10 <sup>14</sup>         |
| <b>photopigment - related measures (α-opic lux) **</b>      |                           |                                 |                                 |
| cyanopic                                                    | 228.34                    | 260.73                          | 671.58                          |
| melanopic                                                   | 256.46                    | 284.92                          | 733.89                          |
| rhodopic                                                    | 283.31                    | 298.75                          | 769.50                          |
| chloropic                                                   | 310.31                    | 320.57                          | 825.70                          |
| erythropic                                                  | 319.04                    | 323.75                          | 833.90                          |
| <b>technical specifications (light sources)</b>             |                           |                                 |                                 |
| lamp technology                                             | fluorescent lamp          | high intensity discharge lamp   |                                 |
| lamp producer and lamp type                                 | Sylvania T5 FHO           | Philips MSR 575 HR              |                                 |
| lamp power (watts)                                          | 39                        | 575                             |                                 |
| luminous flux (lumen)                                       | 2990                      | 49000                           |                                 |
| correlated color temperature (Kelvin)                       | 5000                      | 6000                            |                                 |
| color rendering index (Ra)                                  | 85                        | 90                              |                                 |

shown in Table 1 and Fig. 3.

## 2.2. Test battery

Subjective ratings of ambient room qualities, different emotional states, and symptoms related to feelings of claustrophobia as well as decision-making behavior were recorded.

### 2.2.1. Ambient room qualities

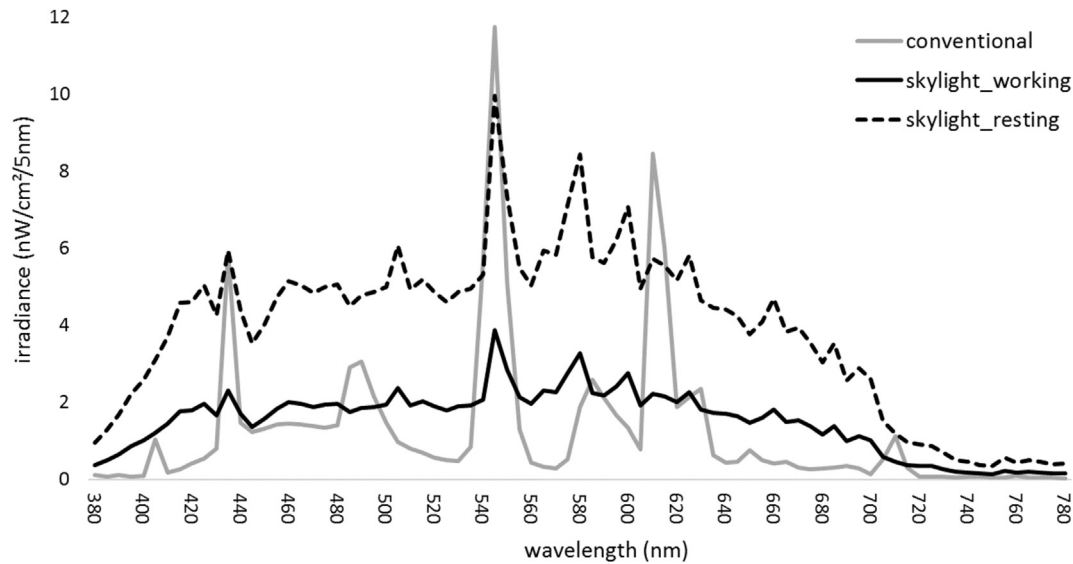
**2.2.1.1. Perceived room atmosphere.** The two test environments were evaluated with a room atmosphere questionnaire developed by Vogels et al. [35]. The questionnaire comprises 38 atmosphere terms that are rated on a 4-point scale (1 = not at all; 2 = little; 3 = rather; 4 = very). By averaging scores, items were summarized according to the four room atmosphere factors, “coziness” (13 items; e.g., pleasant, calm), “liveliness” (8 items; e.g., inspiring, stimulating), “tenseness” (12 items; e.g., oppressive, threatening) and “detachment” (5 items; e.g., formal, business-like).

**2.2.1.2. Connectedness-to-nature scale.** Subjects rated perceived connectedness-to-nature with a single item (“How connected do you feel to the nature now?”) on a 4-point scale (1 = not at all; 2 = little; 3 = rather; 4 = very).

**2.2.1.3. Perceived restorativeness.** The perceived restorativeness scale [36] was used. This scale measures four dimensions of a restorative environment: “being away”, “fascination”, “coherence” and “compatibility”. Due to the laboratory setting of our investigation, we only selected items assigned to the dimension “fascination” (e.g., “the setting has fascinating qualities”, “my attention is drawn to many interesting things”), which were rated on a 7-point scale by the subjects. Ratings were added to derive a total fascination score ranging from –8 to 40.

### 2.2.2. Emotional state

**2.2.2.1. Mood state.** An adjective checklist consisting of 161 items [37], which had to be filled out on a dichotomous scale (0 = no;



**Fig. 3.** Light spectrum at eye level under conventional illumination (grey line; labeled “conventional” in the figure legend), and under skylight illumination while filling out questionnaires and performance tests on the computer screen (solid black line; labeled “skylight\_working” in the figure legend) or while resting (dashed black line; labeled “skylight\_resting” in the figure legend).

1 = yes), was utilized for the study. By averaging scores, the following seven mood state dimensions could be quantified: “performance-related activity” (25 items; e.g., diligent, concentrated), “extraversion” (9 items; e.g., sociable, talkative), “introversion” (8 items; e.g., taciturn, reserved), “general well-being” (24 items; e.g., happy, unworried), “general deactivation” (32 items; e.g., sluggish, exhausted), “tenseness” (26 items; e.g., restless, touchy), and “anxiety and depression” (37 items; e.g., depressed, fearful). Three out of these seven dimensions (i.e., “performance-related activity”, “extraversion”, and “general well-being”) were averaged to derive a positive mood state score. The remaining mood state dimensions (i.e., “general deactivation”, “introversion”, “tenseness”, and “anxiety and depression”) were averaged to a negative mood state score. Mean mood scale values ranged from 0 to 1.

**2.2.2.2. Stress state.** The Dundee Stress State Questionnaire [38] was used to explore stress responses in working environments on the following three dimensions: “task engagement”, “distress”, and “worry”. Again, due to the laboratory setting of our study, two arousal-related subscales of this questionnaire were applied, “energetic arousal” of the stress state dimension “task engagement” (8 items; e.g., alert, active) and “tense arousal” of the stress state dimension “distress” (8 items; e.g., nervous, tense). Items are rated on a 5-point scale (1 = not at all; 2 = a little bit; 3 = somewhat; 4 = very much; 5 = extremely), and subsequently, mean scores are calculated for the two subscales.

**2.2.2.3. Anxiety state.** The State-Trait Anxiety Inventory [39] measures the presence and severity of perceived symptoms of anxiety. It consists of 40 items that are rated on a 4-point Likert scale (1 = not at all, 2 = a little, 3 = somewhat, 4 = very much). In the present study, the state anxiety subscale (20 items) was used. The total state anxiety score ranged from 20 to 80, with higher scores indicating greater levels of anxiety.

**2.2.2.4. Claustrophobic symptoms.** Subjects rated 6 items (“I think that I must leave the room”, “I feel pain and constriction in my chest”, “I perspire more than usual”, “I feel dizzy”, “I feel my heart racing”, and “I feel I do not get enough air”), which are related to

feelings of claustrophobia and are typically perceived when staying in a closed room for a longer time. Items are rated on a 4-point Likert scale (1 = not at all; 2 = little; 3 = rather; 4 = very) and averaged to derive an overall score.

### 2.2.3. Decision making

**2.2.3.1. Game of dice task.** The Game of Dice Task [40] was used to assess decision making in a gambling situation with explicit rules for gains and losses, and stable winning probabilities.

Participants started with a fictitious amount of money (1.000€) and were instructed that they should try to maximize their starting capital. In each of the 18 rounds, participants were required to guess which number will appear on top of a virtual die in the next throw, by betting on a single number or a pre-defined combination of two, three, or four numbers. They won some virtual money if the thrown number matched the single number or one of the numbers among the chosen combination; otherwise, they lost the same amount of money. Each alternative option was associated with the following defined win/loss and different winning probabilities: single number (winning probability: 17%, possible gain/loss 1.000€); a combination of two numbers (winning probability: 33%, possible gain/loss 500€); three numbers (winning probability: 50%, possible gain/loss 200€); and four numbers (winning probability: 67%, possible gain/loss 100€). Before the task started, participants were instructed about the rules, and the possible gain and loss associated with each choice. The number of remaining rounds and the overall capital were permanently displayed on the screen. After each trial, feedback was given about the resulting gain or loss.

The different alternatives were classified into higher risk decisions when the winning probability was below 34% (single number and two number combinations), and lower risk decisions when the winning probability was 50% or higher (combinations of three or four numbers). The net score was calculated by subtracting the number of higher-risk from those of lower-risk decisions. Higher net scores indicated a preference for lower risk options and risk aversive decision behavior.

**2.2.3.2. Ultimatum game.** The ultimatum game [41] measures selfish and fair bargaining behavior. In the two-player game

version, Player 1 suggests how to split a sum of money and Player 2 accepts or rejects the offer. If the offer is rejected, neither player gets anything. The goal of the game is to maximize the amount of won money by each player. In the ultimatum game, the selfish motive to maximize one's gains conflicts with fairness preferences. The rational solution for Player 1 is to offer the smallest possible share and for Player 2 to accept this share. However, the power of refusal of Player 2 forces Player 1 to submit a fair offer, and thus the most frequent outcome of this game is a fair share.

In the present study, subjects played a computerized version of the two-player Ultimatum Game solely in the role of Player 1. Subjects were told that they had to participate in a web-based online-game and that they had to play 12 rounds with 12 different Player 2s, whose monochrome faces were shown on the PC monitor. Photos of Player 2 depicted emotionally neutral faces of six female and six male Caucasians aged 20–30 years (photos were retrieved from a large database of face pictures [42]). In each round, an imaginary sum of 50€ had to be divided between the subject and the online Player 2 as per six pre-defined division ratios, i.e., the subject could either offer 25€, 22€, 20€, 17€, 15€, or 12€ of the fictitious 50€ to Player 2. The probability of rejecting the offer by Player 2 was pre-defined as follows, and it occurred with a certain likelihood: 90% rejection rate for an offer of 12€, 80% for an offer of 15€, 60% for an offer of 17€, 40% for an offer of 20€, and 20% for an offer of 22€. In contrast, a fair offer of 25€ was always accepted by the fictitious Player 2. Subjects received immediate feedback about rejection or acceptance of their offers in each round and they could constantly see the amount of money they had won so far and the money jointly won by the takers on the screen.

The goal of the game was to maximize the amount of money after playing 12 rounds. The mean offered shares and time taken for proposing offers were subjected to analysis. As the time data were skewed, they were log-transformed before being statistically analyzed.

### 2.3. Study protocol

Data collection took place in July and August 2014, from 9am to 5pm. During data collection, the test instructor was not present in the test rooms but a software issued instructions for performing the test and questionnaires and starting the resting periods. Two test subjects participated in the investigation in each test room simultaneously. Subjects stayed in the rooms for 72 min. They were instructed to avoid talking and to remain seated during data collection. The performance tests and recovery phases alternated during data collection. Recovery lasted for 2–5 min, and subjects were informed that they should not close their eyes.

At the beginning of data collection (see Fig. 4), subjects adapted to the test ambience in a resting position for 5 min. Afterwards they had to rate perceived ambient room qualities, their emotional state, and perceived environmental restorativeness. Subsequently, the performance in decision making was measured with different computer tasks. After completing these tests, subjects had to rate their stress and anxiety states, and indicate perceived claustrophobic symptoms. At the end of the test procedure, ratings of ambient room qualities and overall emotional state were collected again. Repeated measures allowed us to quantify changes over time. A detailed time schedule of the study procedure has been shown in Fig. 4.

The study was conducted in accordance with the recommendations of the 1964 Declaration of Helsinki and was approved by the ethics committee of the University of Innsbruck, Austria. Informed consent was obtained from all participants prior to study participation.

### 2.4. Statistical analyses

Independent-samples t-tests were run to determine differences in subjective ratings and decision making tests, which were collected once in each mock-up room. The gender distribution in the two lighting groups was analyzed using the Pearson's Chi-squared test.

Additionally, two-way mixed analyses of variance with the within-subject factor time (2 levels: beginning and end) and the between-subject factor room light condition (2 levels: conventional illumination and skylight illumination) were run to determine the effect of room light interventions over time. If the assumption of sphericity was violated, a Greenhouse-Geisser correction was applied. Skewed reaction times were log-transformed prior to analyses.

The data reported in the subsequent sections are mean  $\pm$  standard deviation, unless otherwise stated. Cohen's  $d$  and partial eta-squared ( $\eta_p^2$ ) document effect sizes with small ( $0.2 \leq d < 0.5$ ;  $0.01 \leq \eta_p^2 < 0.06$ ), medium ( $0.5 \leq d < 0.8$ ;  $0.06 \leq \eta_p^2 < 0.14$ ) and large ( $d \geq 0.8$ ;  $\eta_p^2 \geq 0.14$ ) effects, respectively.

The two-tailed significance level of  $< 0.05$  was assumed for all statistical tests.

## 3. Results

A total of 100 subjects participated in the study ( $n = 50$  subjects were randomly assigned to each lighting condition). The mean age of subjects did not differ under both lighting conditions (skylight illumination:  $25.40 \pm 5.57$  years; conventional illumination:

| TIME [min] | TASK                                                                                        |
|------------|---------------------------------------------------------------------------------------------|
| 0 - 5      | Room and illumination adaptation phase                                                      |
| 5 -20      | <b>Emotional States &amp; Perceived room atmosphere &amp; Connectedness-to-nature scale</b> |
| 20-22      | Recovery                                                                                    |
| 22-25      | <b>Perceived restorativeness</b>                                                            |
| 25-28      | Recovery                                                                                    |
| 28-33      | <b>Ultimatum game</b>                                                                       |
| 33-36      | Recovery                                                                                    |
| 36-41      | <b>Game of dice task</b>                                                                    |
| 41-45      | Recovery                                                                                    |
| 45-48      | <b>Stress State</b>                                                                         |
| 48-51      | Recovery                                                                                    |
| 51-54      | <b>Anxiety State &amp; Claustrophobic symptoms</b>                                          |
| 54-57      | Recovery                                                                                    |
| 57-72      | <b>Emotional States &amp; Perceived room atmosphere &amp; Connectedness-to-nature scale</b> |

Fig. 4. Schedule for the test procedure.

26.40 ± 5.77 years;  $t(98) = -0.887$ ,  $p = 0.377$ ). Gender distribution in the two groups assigned to different lighting conditions did not differ either (skylight illumination: 30 female; conventional illumination: 25 female;  $\chi^2(1) = 1.010$ ;  $p = 0.315$ ).

### 3.1. Ambient room qualities

#### 3.1.1. Perceived room atmosphere

Under skylight illumination, subjects rated ambient liveliness significantly higher ( $F(1,98) = 5.015$ ,  $p = 0.027$ ,  $\eta^2 = 0.049$ ), and ambient tenseness and detachment significantly lower (tenseness:  $F(1,98) = 11.365$ ,  $p = 0.001$ ,  $\eta^2 = 0.104$ ; detachment:  $F(1,98) = 4.426$ ,  $p = 0.038$ ,  $\eta^2 = 0.043$ ) as compared to those in conventional illumination. Ratings for perceived ambient coziness did not differ between the two room lighting conditions ( $F(1,98) = 1.781$ ,  $p = 0.185$ ). Additionally, interaction effects between light and time, and main effects of time did not reach significance level (all  $p > 0.10$ ) in all four room atmosphere dimensions.

#### 3.1.2. Connectedness-to-Nature

Study participants felt a significantly stronger connection to the nature under the skylight illumination:  $F(1,98) = 15.386$ ,  $p < 0.001$ ,  $\eta^2 = 0.136$ . We could not reveal a significant interaction or main effect of time (interaction:  $F(1,98) = 1.642$ ,  $p = 0.203$ ; time:  $F(1,98) = 0.730$ ,  $p = 0.395$ ).

#### 3.1.3. Perceived restorativeness

Ambient “fascination”-scores were significantly higher under skylight than they were under conventional illumination ( $t(98) = 2.718$ ,  $p = 0.008$ ,  $d = 0.54$ ).

In Table 2, the descriptive statistics for the three ambient room quality scales have been summarized.

### 3.2. Emotional states

#### 3.2.1. Mood states

Positive mood states were significantly higher ( $F(1,98) = 5.063$ ,  $p = 0.027$ ;  $\eta^2 = 0.049$ ) and negative mood states were significantly lower ( $F(1,98) = 6.627$ ,  $p = 0.012$ ;  $\eta^2 = 0.063$ ) under skylight as compared to those under conventional illumination. In both lighting conditions, the positive mood state significantly dropped over time ( $F(1,98) = 20.160$ ,  $p < 0.001$ ;  $\eta^2 = 0.171$ ) and the negative mood states rose over time ( $F(1,98) = 6.138$ ,  $p = 0.015$ ;  $\eta^2 = 0.059$ ). The interaction between the factors light and time did not reach

significance (positive mood:  $F(1,98) = 2.407$ ,  $p = 0.124$ ); negative mood:  $F(1,98) = 0.724$ ,  $p = 0.397$ ).

#### 3.2.2. Stress states

Tense arousal was rated significantly lower under skylight compared to conventional illumination ( $t(98) = -2.689$ ;  $p = 0.008$ ;  $d = 0.54$ ). No significant difference in perceived “energetic arousal” could be revealed between the two lighting conditions ( $t(98) = 1.090$ ;  $p = 0.279$ ).

#### 3.2.3. Anxiety state

Anxiety scores were also significantly lower under skylight illumination ( $t(98) = -2.190$ ;  $p = 0.031$ ;  $d = 0.44$ ).

#### 3.2.4. Claustrophobic symptoms

Subjects perceived significantly less claustrophobic symptoms under skylight compared to conventional illumination ( $t(98) = -2.283$ ,  $p = 0.025$ ,  $d = 0.45$ ).

In Table 3, all descriptive statistics for measured mood states have been summarized.

### 3.3. Decision-making behavior

#### 3.3.1. Game of dice task

The net score was significantly lower under skylight illumination ( $4.28 \pm 9.08$ ) as compared to that under conventional illumination ( $8.16 \pm 8.45$ ),  $t(98) = -2.211$ ,  $p = 0.029$ ,  $d = 0.44$ .

#### 3.3.2. Ultimatum game

Offered share was significantly lower under skylight illumination ( $21.00 \pm 1.60\%$ ) as compared to that under conventional illumination ( $21.97 \pm 2.08\%$ ),  $t(98) = -2.594$ ,  $p = 0.011$ ,  $d = 0.52$ . Furthermore, the log-transformed time taken for proposing offers was significantly shorter under skylight illumination ( $3.53 \pm 0.16$  msec) as compared to that under conventional illumination ( $3.61 \pm 0.17$  msec),  $t(98) = -2.638$ ,  $p = 0.010$ ,  $d = 0.53$ .

## 4. Discussion

Study results indicate that, under the artificial skylight, subjects felt more connected to the nature and perceived the windowless test room as more “lively”, and less “tense” and “detached” as compared to fluorescent illumination. Additionally, study participants rated the test environment as more fascinating and reported feelings of lower tension, anxiety, and claustrophobic symptoms. Furthermore, under artificial skylight, positive mood state (i.e., performance-related activity, general-wellbeing, and extraversion)

**Table 2**

Descriptive statistics for the scales “perceived room atmosphere”, “connectedness-to-nature”, and “perceived restorativeness”. Data are mean ± standard deviation. Beginning = measurement after 5 min’ stay in the test room; End = measurement after 75 min’ stay in the test room.

|                                  | Time  | skylight illumination | conventional illumination |
|----------------------------------|-------|-----------------------|---------------------------|
| <b>Perceived Room Atmosphere</b> |       |                       |                           |
| Coziness                         | Begin | 1.75 ± 0.55           | 1.56 ± 0.52               |
|                                  | End   | 1.65 ± 0.60           | 1.57 ± 0.53               |
| Liveliness                       | Begin | 1.83 ± 0.59           | 1.53 ± 0.56               |
|                                  | End   | 1.76 ± 0.70           | 1.53 ± 0.62               |
| Tenseness                        | Begin | 1.61 ± 0.47           | 1.94 ± 0.55               |
|                                  | End   | 1.65 ± 0.54           | 2.02 ± 0.65               |
| Detachment                       | Begin | 2.58 ± 0.66           | 2.84 ± 0.64               |
|                                  | End   | 2.68 ± 0.80           | 2.97 ± 0.76               |
| <b>Connectedness-To-Nature</b>   |       |                       |                           |
| Rating                           | Begin | 1.56 ± 0.73           | 1.08 ± 0.27               |
|                                  | End   | 1.46 ± 0.79           | 1.10 ± 0.36               |
| <b>Perceived Restorativeness</b> |       |                       |                           |
| fascination                      |       | 8.68 ± 10.73          | 3.04 ± 10.01              |

**Table 3**

Descriptive statistics for the emotional state scales. Data are mean ± standard deviation. Beginning = measurement after 5 min’ stay in the test room; End = measurement after 75 min’ stay in the test room.

|                                | Time  | skylight illumination | conventional illumination |
|--------------------------------|-------|-----------------------|---------------------------|
| <b>Mood states</b>             |       |                       |                           |
| positive mood state            | Begin | 0.59 ± 0.23           | 0.51 ± 0.23               |
|                                | End   | 0.54 ± 0.26           | 0.41 ± 0.25               |
| negative mood state            | Begin | 0.18 ± 0.14           | 0.26 ± 0.17               |
|                                | End   | 0.20 ± 0.17           | 0.30 ± 0.20               |
| <b>Stress States</b>           |       |                       |                           |
| tense arousal                  |       | 3.00 ± 0.79           | 2.84 ± 0.67               |
| energetic arousal              |       | 1.85 ± 0.56           | 2.17 ± 0.62               |
| <b>Anxiety State</b>           |       |                       |                           |
| overall score                  |       | 38.24 ± 8.94          | 42.22 ± 9.23              |
| <b>Claustrophobic Symptoms</b> |       |                       |                           |
| overall score                  |       | 1.16 ± 0.31           | 1.33 ± 0.43               |

was significantly higher, whereas negative mood state (i.e., general deactivation, tenseness, introversion, and anxiety and depression) was lower as compared to that under conventional room lighting.

Two theories from the field of environmental psychology, which were developed to explain the beneficial effects of exposure to the nature (e.g., woods, parks), can be utilized to understand the present results of the effect of artificial skylight in a windowless environment. The psycho-evolutionary theory [43] proposes that exposure to natural environments initiates an immediate positive affective response. The attention restoration theory [44] suggests that “softly” fascinating environmental stimuli, typically perceived in natural environments, promote feelings and thoughts of being-away-from-daily-routines, and thus, they have a restorative effect. The present study validates these suggested effects of natural environments of both theories in a windowless indoor environment. It can be assumed that looking at an artificial indefinite sky and being exposed to artificial sunlight profoundly increased the perceived naturalness of the windowless test environment and directly altered mood states of study participants.

There is mounting evidence that people feel tense, entrapped, and sometimes perceive claustrophobic symptoms when staying in windowless spaces for a longer period (e.g., [45–47]). Additionally, subjects staying in a closed room respond with more pronounced cortisol reactivity to stress induction [48].

Today, people in Europe, Canada, and North America spend 50–85% [49,50] of their time in indoor environments and a substantial amount of these environments have restricted amount of daylight. For instance, a recently published survey of 3600 office workers in seven European countries and the United Arab Emirates [51] reported that 7% of their office workspaces had no window view, and 42% had to switch on artificial lights because of insufficient daylight.

It has been reported [52–54] that workers commonly compensate for a lack of windows by bringing potted plants and pictures of nature into their workplaces. Integration of daylight-substituting lighting technologies may offer another option. Commonly, these technologies change light intensities and color temperatures during the day, and thus provide an abstract and technical substitute for daylight. The present study could demonstrate that an artificial skylight, which perfectly mimicked the photometrical features of the visible portion of sunlight and skylight and which gave a virtual impression of a building opening, unambiguously mitigated negative feelings of staying in windowless environments (e.g., feelings of increased tension, anxiety, and claustrophobic symptoms) and increased feelings of being in contact with the nature.

In line with our hypothesis, subjects made riskier decisions in a windowless environment with artificial skylight illumination as compared to those made in an environment with conventional fluorescent illumination.

It can be assumed, and is confirmed by previous research (e.g., focusing on affect heuristics [55], affective congruence [56], and risk-as-feelings [57]), that altered mood states of subjects under the artificial skylight (e.g., lower state anxiety and feelings of tension, and higher perceived well-being and extraversion) may have affected their decision-making behavior. Briefly, negative mood states may have provoked an attentional/cognitive bias towards potential adverse outcomes, and consequently, they may have led subjects to exhibit more risk averse behavior and to choose safer options [58,59]. In contrast, positive mood states probably have induced a higher risk tolerance, and thus, they were found to result in riskier decision-making behavior [29].

Furthermore, using the ultimatum game as a method to study conflicts in social decisions, we found that subjects showed more selfish bargaining behavior and faster decision times in offering

shares under the artificial skylight as compared to those in conventional fluorescent illumination. Previously, empirical findings lent support to the hypothesis that different mood states can have an influence on social decisions involving selfishness versus fairness. Specifically, several studies showed that positive mood states induce a more optimistic, confident, faster, and less polite decision-making behavior [60,61], whereas negative mood states produce a more cautious, pessimistic, slower and socially constrained behavior [62–64]. Therefore, our results corroborate these previous findings, since the different mood states of the subjects under the two lighting conditions may have biased the social decision-making behavior.

One has to keep in mind that, in the current study, different factors may have influenced the results. From a perceptual point of view, several apparent features of the artificial skylight (e.g., the solid angle of the artificial sun, parallax phenomenon, 3D-depth) may have led to the impression that a real skylight was integrated in the test room. Currently, little is known about non-visual light effects caused by a fictitious view-through experience [18,20]. Additionally, subjects were exposed to direct artificial sunlight and consequently higher photopic/melanopic lux levels (see Table 1) during the resting periods. Research indicates that exposure to higher light levels during the day may elicit effects on perceived vitality and alertness [65,66], cognitive performance [65,67], and several physiological parameters [65,67]. Furthermore, there is evidence for daytime light effects caused by light spectra with an increased portion of short-wavelengths on working memory tasks, attention, and arousal [68,69].

Taken together, these facts and the present findings that artificial skylight generated a surprisingly natural view to a fictitious sky in a windowless test environment and that subjects were regularly exposed to bright light while resting, it can be assumed that both, the visual features of the artificial skylight and the regular exposures to bright light, are responsible for the documented light effects.

Our study has several limitations. First, we did not incorporate a real skylight condition with higher luminances and exposure to infrared radiation in our study protocol. Consequently, potential differences in the effects of a real skylight compared to artificial skylight remain unknown. Second, the position of the artificial sun was stable over time and only a restricted room area (i.e., resting area) was directly lit by artificial sunlight. On one hand, the present study design guaranteed that discomfort glare was avoided when subjects filled out questionnaires and performed tests on the computer screen; while on the other hand, it facilitated exposure to bright light while subjects rested. Further, as data collection lasted only for 1.5 h, it can be assumed that the static position of the sun was hardly noticed by study participants. However, we do not know if longer exposure duration under a static skylight (in terms of the position of the artificial sun and weather conditions) may have an impact on study outcomes. Third, only temporary light effects under highly controlled laboratory conditions were measured in the present study. Thus, long-term effects (e.g., spanning several days) of this artificial skylight under naturalistic working conditions remain unclear.

## 5. Conclusions

Nowadays, humans spend an expanded amount of time in windowless environments, especially when they live or work in densely built urban areas. Understanding the potential detrimental effects of staying in these environments is therefore of importance.

Daylight substituting lighting technologies may help to compensate for a lack of windows and exposure to natural light.

The present study, for the first time, demonstrated the beneficial

effects of artificial skylight on several scales of negative as well as positive mood states in a windowless office environment. It can be hypothesized that the riskier and more selfish decision-making behavior that was observed in the present study under the artificial skylight was mediated by altered mood states.

Whether the artificial skylight deploys the described effects outside the lab, in daylight-deprived spaces, must be substantiated in further long-term studies that are implemented in naturalistic conditions.

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## Conflict of interest

The persons involved in the development of the artificial skylight system were neither involved in designing the study, collecting and analysing data nor publishing the results. Two authors (M.C. and W.P.) are employed at the R&D and lighting design company Bartenbach GmbH (Aldrans, Austria). The authors report no conflict of interest.

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