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Publication Date
2020-07-01

DOI
10.1016/j.buildenv.2020.107060

Experimental evaluation of visual flicker caused by ceiling fans

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Abstract
Significant energy savings can be achieved by promoting elevated air speed using ceiling fans by increasing the cooling set-point temperature of an air-conditioning system. However, fan blades that obstruct the light from an artificial ceiling fixture from the relative viewing position of a building occupant could causes problems of visual flicker. We performed experiment to identify the effects of visual flicker caused by ceiling fans. Two different designs were used that had either opaque or transparent blades, which created different levels of visual flicker. These were installed in two test-rooms with similar environmental conditions. Forty-six participants took part in the study under a crossover design. Participants completed three cognitive visual tasks in both conditions: Stroop-test, switcher and digit-span tasks, respectively. Before and after completing the tasks, subjective evaluations were also given to several variables. Comparisons across the two ceiling fans showed the following results: a small and just significant reduction of performance in the digit-span task but not for the Stroop-test and switcher-task; some adverse symptoms related to visual flicker, which were not found when directly comparing the two ceiling fans against each other; and a higher reported frequency of discomfort caused by visual flicker. While the effect we uncovered in our study was small and did not influence all parameters, the exposure to visual flicker was relative short and we do not yet know how building occupants may react across a longer period. If issues of visual flicker are not addressed, it may have adverse consequences on building occupants.

Keywords: Ceiling fans; Cognitive performance; Vision; Visual flicker

1. Introduction

Electrical energy used by air-conditioning systems accounts for 60 % of the total energy used in commercial Singaporean buildings [1,2]. Electric fans that elevate airspeed can significantly reduce this reliance and the energy demands placed on air-conditioning [3,4]. Specifically, when ceiling fans are utilised, the temperature setting of a Singaporean air-conditioned building could be raised from 23 to 26 ^{o}C (or higher), resulting in higher perceived levels of thermal comfort and a substantial reduction in energy use [5]. While the application of fans in Singapore and other tropical climates has shown promising results, most studies (e.g. [5–8]) only consider the thermal needs of people. Other environmental conditions, such as light can have significant impacts on the occupant comfort, health and productivity as well as on energy usage [9], but are often overlooked.

We think that the overall performance of any ceiling fan should be assessed by evaluating the impacts it has on both the human thermal and visual system. When a ceiling fan is positioned under an artificial light installation (Figure 1), the swept area of a rotating fan blade can frequently block the light source(s) creating a risk of visual flicker [10]. Visual flicker is usually described by the changes in modulation depth (MD) (i.e. peak-trough) across time (i.e. frequency) in electrical or luminous output of an artificial light source [11]. When dealing with ceiling fans, visual flicker is associated with the changes in MD and frequency that occur when the luminous output is interrupted by the blades from the perspective viewing position.

Figure 1. Examples of visual flicker caused when the artificial light installations are placed above the mounting height of the ceiling fan. From certain viewing positions as seen in: (a) classroom, (b) Hawker (food court) centre, (c) outdoor café and (d) gymnasium, the fan blades will obstruct the illuminated area of the light fixture and causes visual flicker.

Visual flicker has an significant impact on human health and well-being [12]. The phenomenon of visual flicker can be divided into two categories: visible flicker (from ~3 to ~70 Hz) and invisible (imperceptible) flicker (≳70 Hz) [13]. The threshold above which visual flicker is no longer perceived (i.e., the transition point between visible and imperceptible flicker) is known as the critical flicker (fusion) frequency [14,15]. Visible flicker is both sensed and perceived by the human body, whereas invisible flicker is not perceived but the luminous modulation can still be sensed and can cause negative health effects (i.e. headaches and eyestrain) [11,16]. These effects are less likely to occur when flicker is within the invisible range of frequencies than when it can be perceived by the observer [17].

https://doi.org/10.1016/j.buildenv.2020.107060
https://escholarship.org/uc/item/3wj1f6xj

MD can be defined by the Michelson contrast, which takes into consideration the maximum (L_{max}) and minimum (L_{min}) luminances of the light source in a single frequency cycle [18] and is calculated according to (1) [19]:

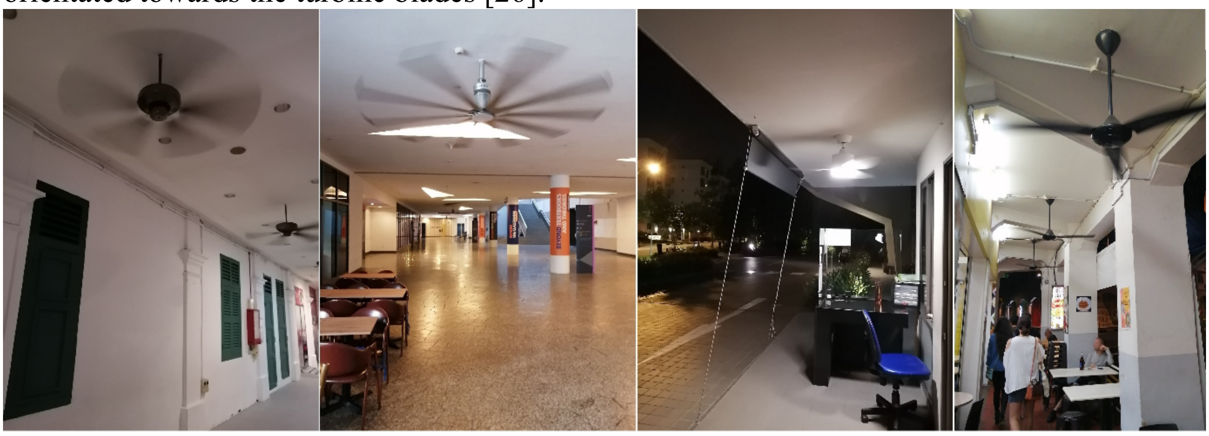
$$MD = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \; 0 \leq MD \leq 1 \; and \, MD \in \mathbb{R} \tag{1}$$

According to Wilkins *et al.* [13], the effects of modulation within the range of imperceptible flicker have not been well documented. However, at MDs ranging from 0.27 to 0.33 and a frequency rate of 100 Hz, flicker from electric lighting is known to cause headaches [16]. Perz *et al.* (Perz et al., 2017) showed that peak sensitivity values of flicker occur at approximately 15 Hz with an MD of 0.002, whereby light modulations were created by overhead electric fixtures within a large portion of the observers' visual field.

Although lighting standards (e.g. [20–22]) address issues of flicker, these are only related to the operation and maintenance of artificial lighting (i.e., ensuring high operational frequencies around 30 kHz). Although MD is not often used to distinguish between high and low flicker, Wilkins *et al.* [13] state that, at sufficiently high frequencies, there are limited concerns that flicker will impact human health and well-being. On the other hand, the frequency ranges that cause visual flicker from the operation of ceiling fans (from ~3 to ~8 Hz) depending on the rotational speed) are significantly lower than these design values. Although these values may pose a risk of causing visual flicker in buildings, there are few studies that have addressed this issue when evaluating the performance of ceiling fans.

A study in a Japanese classroom with ceiling fans found that 26 % of the students (*n*= 36) reported issues of flicker and 61 % found ceilings fans unpleasant to observer [23]. Survey responses from engineers, faculty and architects revealed 54 % mentioned aesthetics as an important topic related to the active use of ceiling fans (i.e., how ceiling fans change the visual impression of a space), 46 % discussed the challenges of mounting the ceiling fans in coordination the light fixtures to prevent them from swaying or causing flicker, and 23 % raised issues of ceiling height limitations [24].

Besides ceiling fans, visual flicker has also been identified when wind turbines are operated [25], whereby the movement of the blades continuously block incident sunlight and cast moving shadows. According to the authors, most three bladed turbines can produce flicker at a rate of 3 Hz. This can cause problems in rooms or buildings with windows that are orientated towards the turbine blades [26].



(a) Wagon-wheel effect | (b) Wagon-wheel effect and visual flickering | (c) Shadow effect from down-lighting | (d) Shadow effect from side-lighting

Figure 2. Examples of: (a) A ceiling fan showing the wagon-wheel effect, (b) a ceiling fan showing the wagon-wheel effect and producing visual flicker, (c) a ceiling fan with reflected down-lighting causing shadowing, and (d) a ceiling fan with side-lighting causing shadowing.

To remove the risk of flicker, an ideal scenario might be to mount the ceiling fans at the same height as the artificial lighting fixtures. However, in spaces that have certain constraints (e.g., low floor-to-ceiling height, limited available ceiling area, or the use of suspend lighting may not appropriate), the ceiling fans are mounted below the artificial fixtures. This approach also allows ceiling fans to be easily retrofitted into existing buildings. When the ceiling fan is mounted below the artificial fixture, it is recommended that they are placed away from the light source to reduce flicker [27]. Figure 1 shows that this does not consider the visual parallax effect (i.e., the location of the ceiling fan and artificial light fixture relative to the viewing position of the observer) and there is still visual flicker.

Nevertheless, this design consideration has been recommended to avoid strobing [28,29], whereby the blade crosses the cone of light (i.e., the beam angle created by the fixture) creating constant shadow patterns to appear on the room surfaces. This shadowing effect may also occur when the artificial light fixture is mounted onto the ceiling fan (Figure 2 (c)). The reflection of the light beam in these cases are stronger, because the fixture is closer to the floor, which reflects upwards towards the ceiling and casts a shadow profile of the rotating ceiling fan blades. In lower ambient background lighting (as seen in Figure 2 (c)), this issue is more apparent. This problem is also apparent when side-lighting (wall mounted) fixtures meet the fan blades (Figure 2 (d)).

Ceiling fans also produce other visual effects. The movement of the fan blades at high rotational speeds also creates a phenomenon of visual aliasing (Figure 2 (a) and (b)), which is commonly known as the wagon-wheel effect [30]. This alias may reduce the observer's ability to perceive the movement of the fan blades. In residential homes, unintentional child head injuries have been reported in situations where high furniture (e.g. beds) is too close to ceiling fans [31]. Furyk *et al.* [32] concluded that '*ceiling fans are a small but important source of paediatric head injury*'.

The literature has shown that visual flicker could also have an impact on mental cognition, increase fatigue, and reduce the rate of learning and work performance [33,34]. Veitch and McColl [12] evaluated the influence of two different rates of flicker from artificial light fixtures: lower frequency at 120 Hz and high frequency (from ~20 to ~60 kHz). Visual performance scores were significantly higher when observers completed the visual tasks under the high frequency condition. Therefore, there are reasons to believe that – other than induced discomfort symptoms – ceiling fans may impact on the building occupant's ability to perform work-related tasks.

The frequency at which ceiling fans cause flicker depends on the rotational speed and number of the blades. Rotation speed can vary to ensure comfort within the thermal environment. Conversely, MD is primarily dependent on the physical properties of the ceiling fan (e.g. its opacity or size) and its relative location to ceiling lights, whereby blades that block more light from the artificial fixture(s) – when rotating – will cause more flicker. These parameters are fixed during their operation.

In this article, we aimed to evaluate the potential impact of visual flickering caused by ceiling fans on cognitive performance. To achieve this, a controlled experiment was designed that compared two conditions against each other: a ceiling fan with opaque blades and a comparable condition using transparent blades. Therefore, both conditions used the ceiling fans to elevate the local indoor air velocity to achieve comparable thermal conditions, but differences in visual flicker across the two conditions varied. Since the transparent fan blades do not fully obstruct incident light from ceiling lights, we hypothesised that visual flicker effects commonly associated with ceiling fans would be minimised under this condition. To evaluate the impact of both conditions on test observers, we evaluated cognitive performance and collected ratings given to different survey parameters.

2. Methodology

2.1. Experimental setting

To test our hypothesis, we designed an experiment using two test-rooms. The rooms had the same physical dimensions (4.3 x 5.6 x 2.6 m), furnishing and layout (Figure 3). Two ceiling fans were used in the experiment, which were mounted at the approximate central point of each room. One fan had opaque blades and did not allow light to be transmitted through, while the other design had transparent blades. Herein we refer to the two as the opaque and transparent ceiling fans, respectively. Both fans were three bladed design: the opaque ceiling fan was an Aeratron AE3 model (blade diameter= 1.52 m, hub height from floor= 2.38 m) and the transparent fan was an Artemis Minka-Aire F803L-TL model (blade diameter= 1.47 m, hub height from floor= 2.23 m) (Figure 3). The viewing position of the participant was set so that the fan blades would sweep across the visible area of a ceiling mounted light – labelled flicker source (Figure 3). To create flicker at the viewing position and to avoid the shadowing effect, the tip of the ceiling fan blade was positioned 0.25 m away from the flicker source. For this same reason, the ceiling lights above the participants were switched off.

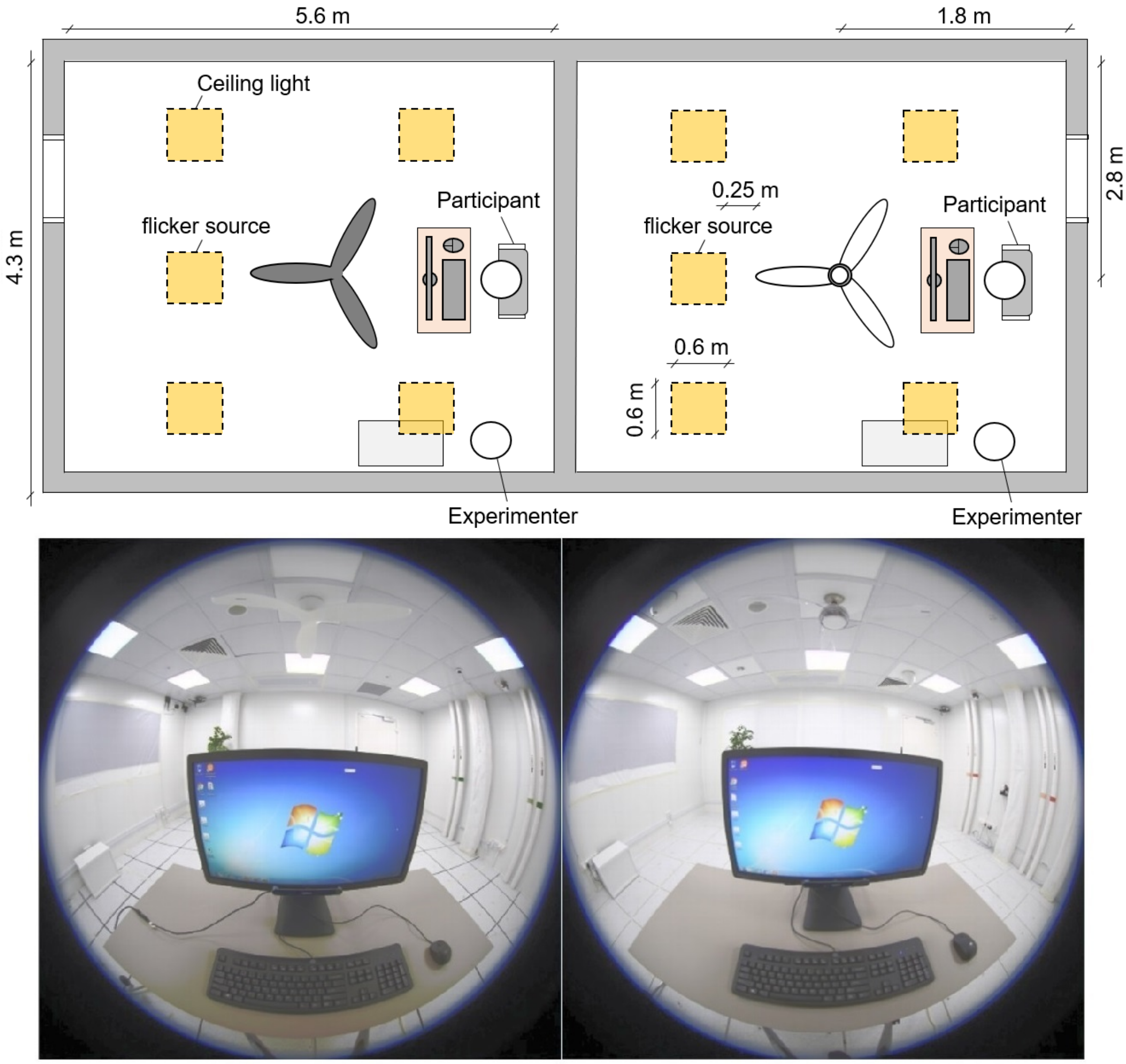


Figure 3. The layout of the two test rooms showing the test participant sat at the workstations and the position of the two ceiling fans: opaque and transparent. Below are shown fisheye images capture at the viewing position of the observers in both test rooms: Opaque ceiling fan (*left*) and transparent ceiling fan (*right*).

To visualise the conditions experienced in both rooms under the two different ceiling fans, we have included a video component (Video 1). This depicts a side-by-side comparison of the rooms as seen from an on-axis (direct) viewing position. From this perceive view, the levels of visual flicker can be seen in the video component. To access the video component, simply click on the image seen below (online version only).

Video 1. A side-by-side comparison of the two test-rooms showing visual flicker being produced from the opaque ceiling fan (*left*) and transparent ceiling fan (*right*).[1]

Since the frequency of flicker produced by the ceiling fan is related to its rotational speed, this was held constant during the experiment. The RPM (revolutions per minute) produced by each ceiling fan at each speed setting was measured using a tachometer (Testo 470, Testo SE & Co. KGaA, Germany). We selected speed settings for both ceiling fans, which produced rotation speeds of 131 RPM (6.6 Hz) in both test-rooms. Due to differences in blade design, the opaque fan rotated clockwise, and transparent fan in an anti-clockwise direction. However, we had no reason to believe that this would influence any conclusions.

2.2. Photometric conditions

Artificial lighting was produced by five 45 W recessed LED panel fixtures in each test-room, whereby each were 0.6 x 0.6 m. We used a chromameter (LS-100, Konica Minolta, Japan) to record illuminances and correlated colour temperatures, a spectrophotometer (MK350NP, UPRTEK, Taiwan) to measure colour rendition, and a luminance meter (MAVO Spot 2, Gossen, Germany) to report surface brightness. To evaluate colour rendition, we used the colour rendering index [35]. Daylight was masked in both test-rooms.

To ensure that the lighting conditions were approximate to each other across the two test-rooms, we measured horizontal grid illumination, horizontal desk illumination, ambient lighting conditions, and evaluated visual discomfort parameters. Horizontal grid measurements were taken across the available floor surfaces of the two rooms at a height elevated at 0.75 m above the floor level. This excluded areas in the two room where furniture prevented accurate readings (i.e., plants, desks, chairs, etc.). To calculate the minimum spacing size between each grid point, we used the method recommended in the EN 12464 and Society of Light and Lighting Handbook [20,36]. The resultant minimum grid spacing calculated was 0.70 m (rounded up to the nearest tenth). To calculate uniformity, we divided the minimum illuminance by the average of all measurements on the horizontal grid [22].

Horizontal desk illumination was measured on the upper surface of the desks found in the two rooms. At three different positions on the desk, measurements of illuminance, colour

[1] FOR REVIEW PURPOSES: Video 1 appears in online version only and not in printed version.

rendition and colour temperature were recorded. To account for error, we repeated the measurements three times at each point and took the average across the values collected.

To measure the ambient background lighting conditions inside the test-rooms, we considered two parameters: the vertical illuminance received at the eye level of the participant and the average luminance of the surfaces seen within their visual field. To map the luminances across the entire visual scene of the participant, seven low dynamic range images with varying shutter-speeds were captured using a Canon 5D camera equipped with a Canon EF 8-15 mm f/4L fisheye lens. These images were merged into a single high dynamic range image (HDRI) using the software Photosphere (Figure 3). The HDRI was processed using Evalglare [37] to evaluate the average background luminance of the test-rooms and discomfort glare. Discomfort glare was analysed using the Unified Glare Rating [38], which is an index suitable for evaluate visual discomfort perceived from artificial lighting. At the viewing position, we also measured the average self-luminance of the computer screens, and the luminance of the artificial light fixture closet to the ceiling fan blade when it was not obstructed.

Table 1 presents the photometric parameters that were recorded in both test-rooms the two different ceiling fans. The measurements show the conditions which were measured on the horizontal grid, on the horizontal desk surface, the ambient background lighting conditions, and the visual discomfort parameters. The horizontal illuminances, uniformity, colour rendering indices, and the Unified Glare Rating values in both rooms conform to recommended levels found in the Singaporean lighting standards [21,22]. Based on the wide range of parameters measured, we concluded that the photometric conditions across the two-rooms were practically the same.

Table 1. Photometric parameters measured in both rooms: one room with the opaque mounted ceiling fan and the other with a transparent ceiling fan

Measured parameter	**Ceiling fan**	
	Opaque	*Transparent*
Horizontal grid measurements		
Average horizontal illuminance (lux)	734	724
Illuminance uniformity (-)	0.56	0.61
Average colour rendering index (-)	82	81
Average correlated colour temperature (K)	5351	5332
Horizontal desk measurements		
Average desk illuminance (lux)	528	526
Average desk colour rendering index (-)	81	81
Average desk correlated colour temperature (K)	5365	5393
Ambient background lighting conditions and visual discomfort		
Illuminance at eye (lux)	408	409
Average luminance of the test-room (cd/m^2)	134	137
Unified Glare Rating (-)	11.90	11.50
Average computer screen self-luminance (cd/m^2)	189	189

Average ceiling lighting luminance (cd/m²)	2561	2565
Average luminance of ceiling fan	151	2363
Weber contrast (-)	0.94	0.08

MD was estimated by positioning the fan blades at two set positions: open (i.e., when the blades did not obstruct any part of the flicker source) and closed (i.e., when the ceiling fan obstructed the largest possible area of the flicker source (Figure 3)). At both positions, spot-point luminance measurements were recorded from the viewing position. At the open position, three measurements across the area of the flicker source were measured and averaged. This luminance value was considered to be the maximum. At the closed position, three measurements underneath the blade (i.e., the surface facing the floor) directly below the flicker source were recorded. Since the blades do not block the whole area of the light fixture, the luminance of the entire flicker source is not modulated by the ceiling fan when it rotates. For this reason, the luminances recorded at the open and closed position were averaged together. This was considered to be the minimum value. This process was repeated for the opaque and transparent blades. For the purposes of providing a comparison across the two ceiling fan conditions, the Weber contrast was used to evaluate the differences in between the average minimum and maximum luminances [39]. To calculate the Weber contrast, the difference between the maximum and minimum luminances were divided by the maximum value.

2.3. Airflow velocities

Although the rotation speed of the ceiling fans was held constant across both test-rooms, we also measured the air velocities to ensure there was no differences in airflow across the two test-rooms. That is, changes in the fan blade design create differences in airflow velocities [40]. We measured elevated air velocities inside both rooms at different locations at four heights from the floor: 0.1, 0.6, 1.1 and 1.7 m, respectively, as recommended in the ASHRAE 55 [41]. At each height, a total of 140 evenly distributed sampled airflow velocity measurements were collected on a horizontal grid in each test-room. Measurements of airflow taken in one test-room were repeated at the approximate position in the other test-room containing a different ceiling fan. To achieve this, we utilised 20 omnidirectional hot-sphere anemometer sensors (SensoAnemo 5100SF, Sensor Electronic, Poland – with an accuracy of ±0.02 m/s and ±1.5 % of readings), which were mounted on a sensor tree [42]. The velocity at each point was an average of samples taken at two second intervals across a five-minute measurement period.

Figure 4 shows the 560 individual airflow velocities (140 points at each of the four measurement heights) recorded in both test-rooms with the transparent ceiling fan (y-axis) and the opaque ceiling fan (x-axis). The data points have been coloured to correspond to the four mounting heights at which measurements were collected. The line across the diagonal of the plot demarcates the null point (i.e. no difference).

Visual observation of Figure 4 generally shows that most of the data points are located relatively close to the null point, which suggests that airflow velocities in both test-rooms were similar to each other. The mean air-velocities aggregated across the four measurement heights were: opaque= 0.68 m/s (SD= 0.37) and transparent= 0.62 m/s (SD= 0.31). We also calculated the Mean Average Error (MAE) of the air-velocities across the two test-rooms according to equation (2):

$$MAE = \frac{\sum_{i=1}^{n} \left| opaque_i - transparent_i \right|}{n} \quad (2)$$

Whereby, $opaque_i$ (m/s) and $transparent_i$ (m/s) are the individual data points paired together based on the same measurement position taken in either test-room, and n is the total number of values recorded (i.e., 140 multiplied by four measurement heights (n= 560)). We concluded that this difference and graphical observation (Figure 4) generally signifies that the air-velocities created by the ceiling fans in both rooms were approximate to each other. However, at 0.10 m from the test-room floor level, Figure 4 shows that the air-velocities created by the opaque ceiling fan were consistently higher. To evaluate if this difference had any unwanted influence, we collected subjective feedback from participants to determine if they had felt any differences in the air-movement created by the two ceiling fan conditions.

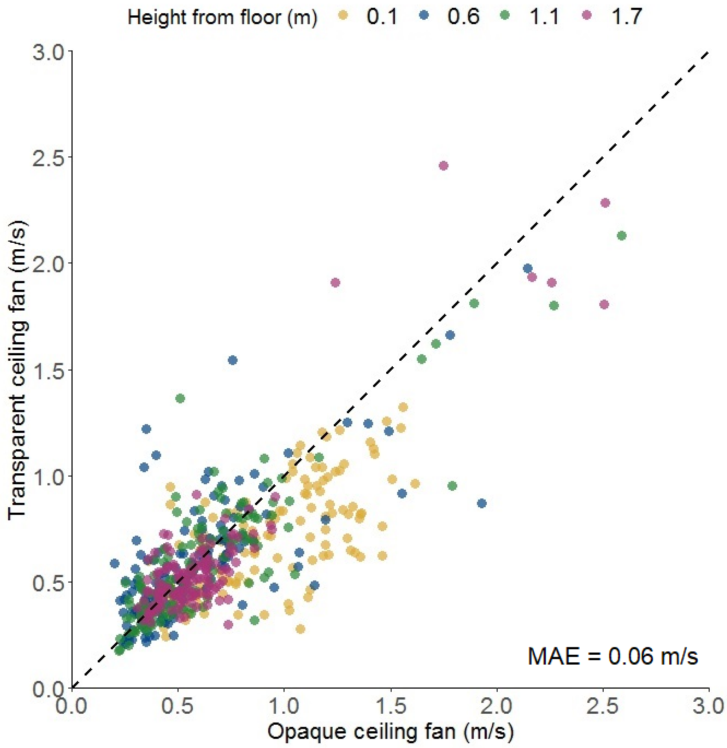


Figure 4. Graph showing the 160 airflow velocities measured at the four measurements heights (0.1, 0.6, 1.1 and 1.7 m, respectively) collected from both test-rooms containing the transparent ceiling fan (y-axis) and the opaque ceiling fan (x-axis). The MAE is shown to indicate the differences in air-velocities. Note: the line across the diagonal of the plot correspond to the null point (no difference).

Other environmental parameters such as dry-bulb air temperature, operative temperature and relative humidity were measured at the workstations at the same position in both test-rooms at one-minute intervals using a data logger (HOBO U12-012, Onset, United States). The maintained temperature range selected in our study was informed by the literature [5], whereby a higher cooling set-point can be used when elevating the localised indoor air-velocities. In our experiment, the temperature was maintained between 26.5 and 27.5 ^{o}C in

https://doi.org/10.1016/j.buildenv.2020.107060
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both test-rooms. In a study that had used an approximate room temperature to ours [5], the preferred air-velocity produced by the ceiling fans at desk level was estimated to be 0.60 m/s. In our study, the average air-velocities measured at 0.60 m from the floor (i.e., the closest height measured to desk level) was 0.58 m/s. Therefore, the effect of visual flicker was evaluated under conditions that may promoted higher levels of thermal comfort and could lead to significant energy savings

2.4. Cognitive performance tasks

We used the Psychology Experiment Building Language (PEBL) software [43] in our experiment [44], which contains a battery of different (visual) cognitive and behaviour tasks. We used three different tasks, namely, the digit-span task, the switcher-task and the colour Stroop-test. Since these tasks are used to test different aspects of cognitive performance, we believe they reflect upon some fundamental mental attributes which are needed to perform daily tasks within indoor environments (e.g., learning in schools). The digit-span is used to test short-term memory by presenting a canonical string of numbers and evaluating the amount that are correctly recalled in the original order that they were presented [45] . The switcher-task tests the ability to switch between different decision rules, which requires selecting and matching a target stimulus based on characteristics of the previous target [44]. The colour Stroop-test evaluates inhibit cognitive inference: i.e., when a specific colour stimulus impedes the information processing of a word stimulus attribute [46].

For the switcher task and Stroop-test, performance scores were measured and independently evaluated using two parameters: rate of completion (speed) and freedom from error (accuracy). Participants that performed the tasks faster and with less errors were considered to have a higher performance. Speed was evaluated by the total time it took participants to complete the task (i.e., duration measured from start to finished), and also by the longest response time recorded; this is defined as the maximum time taken for a participant to respond to one single task stimulus, identified across all other stimuli presented.

For the Stroop-test, accuracy was further subcategorised by the number of correct and incorrect responses, whereby the participants' response can take on either categorisation before the next stimuli appeared on the screen. While for the switch-task, a correct response must always be given before the next stimulus appears. Therefore, the total number of correct responses is always constant for the switcher-task, and the number of incorrect responses and completion times are the only performance measures that vary.

For the digit-span test, the number of correct and incorrect responses and the maximum number length (i.e., the longest canonical string of numbers that were correctly recalled by participants) were evaluated. Because the length of the numbers being recalled also dictates the completion rate, whereby participants that recalled a longer string of numerical values would require more time to complete the test, speed was not evaluated for this task.

All performance measurements were automatically collected by the PEBL software [43] during the experimental procedure.

2.5. Subjective evaluations

We evaluated several different subjective parameters to describe the indoor environmental conditions inside the test-rooms. Ten subjective evaluations were evaluated. The questions were formulated to determine if any of the symptoms were experienced at certain points

https://doi.org/10.1016/j.buildenv.2020.107060
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during the experiment. Variables were measured online using Qualtrics [47], which were displayed at the workstations in the test-rooms.

Two different levels of measurement were used to evaluate the ten subjective items. We used 6-point Likert scales designed to capture 'Right now feedback' from the participants ranging from, 'Not at all' to 'Overwhelming'. These measured seven of the subjective evaluations of, respectively, eye irritation or dryness, headaches, dizziness, fatigue, sleepiness, difficulty concentrating, and difficulty thinking. Discomfort caused by three parameters, namely, air-movement, visual flicker, and the movement of the ceiling fan blades were measured on a 5-point Likert scale ranging from, 'Strongly Disagree' to 'Strongly Agree', which were balanced across a neutral criterion, 'Neither Agree nor Disagree'. On these scales, participants were asked to rate how uncomfortable the follow parameters were.

2.6. Procedure

Forty-six test participants were recruited to take part in the experiment, the mean age of the sample was 29 years (SD= 10.80), 23 were male and 23 were female, 34 participants wore glasses or contact lenses, no participants reported a history of suffering from seizures, epilepsy or migraines, and no participants self-reported that they did not have any form of colour-blindness. Since two of the cognitive visual tasks (switcher and colour Stroop-test) contained colour stimuli, we also tested colour-blindness using the Ishihara test [48]. This test was administered at the beginning of the test upon the arrival of the participant. Participants performed the test in a room predominantly lit by natural light, with the test plate at approximately 0.75 m and perpendicular to their viewing position.

The experimental procedure utilised a crossover design, whereby participants were allocated into a test session sequence based on their demographics (e.g. gender) [49]. Each sequence comprised of two test sessions – each containing a different ceiling fan condition – that lasted one hour each. Test participants were seated in one of the test-rooms and performed the three different cognitive visual tasks and gave their subjective evaluations of the indoor environmental conditions at the start and end of each session. After the first test session, a short intermission period was given outside of the test-rooms of approximately 10 minutes, and the experiment resumed with the participant repeating the test procedures in the alternate test-room. To minimise unwanted procedure effects, the order in which participants completed the experiment was equally balanced. In other words, 23 participants first evaluated the conditions in the test-room with the opaque ceiling fan and then transparent fan. The other 23 participants did the same, but the presentation order of the ceiling fans was reversed. We randomised the order presentation in which the cognitive visual tasks were completed. The participants were not informed of the true nature of the experiment [49], instead they were told that the study aim was to evaluate indoor environmental conditions inside the test-rooms.

The UC Berkeley Committee for Protection of Human Subjects approved the research protocol (CPHS #2019-07-12393).

2.7. Statistical analyses

To analyse the data collected, we used Null Hypothesis Significance Testing (NHST) [50]. This was used to evaluate the differences in performance (i.e., accuracy and speed measurements) and the subjective evaluations measured across the two ceiling fan conditions (opaque and transparent). To denote the levels of statistical significance (i.e., the threshold at which the null hypothesis (no difference) is rejected and alternative hypothesis was accepted), the following classifications were used: weakly significant*, significant**, and highly significant***. Values higher than the maximum threshold representing a weakly significant difference were not considered to be statistically significance (n.s.).

Since data that evaluated rate of speed were collected at a continuous level of measurement, difference testing utilising the mean average parameter were used [51]. To test the assumption of normality, we utilised Quantile-Quantile plots [52] and statistical (Anderson-Darling [53] and Lilliefors [54] tests) analyses to determine if the differences across the two ceiling fan conditions were normal about the mean of their sampling distribution. If this assumption was met, we utilised the paired-samples *t*-test [50]. In cases when normality was violated, the counterpart Wilcoxon signed-rank test was used [55]. This test was also used to evaluate the items measured on the 6-point scales, since the data were collected using Likert scales. To evaluate accuracy, we calculated the percentage of incorrect responses and evaluated the differences – for this indicator of performance – across the two ceiling fan conditions using the same aforementioned inferential tests.

To analyse the subjective evaluations, the semantic labels on the 6-point scales were first transformed to numerical values. For each criterion step change on the three different scales this consistently equated to a difference of one unit (e.g., 'Not at all' corresponded to the lowest value of one and 'Overwhelming' was assigned the highest value of six).

Since the 5-point scales were balanced across a neutral criterion at its centre, we avoided numerical transforming the sematic labels. This was to avoid making any assumptions that the sematic labels towards and at the extreme ends of the scale were diametric to each other (i.e., the interpretation of 'Strongly disagree' was not directly opposite to 'Strongly agree') [56]. Instead the frequencies in which participants reported each criterion on the scale were evaluated. We combined the evaluations given to 'Strongly agree' and 'Agree' to represent 'Agreed', and the same process was applied on the opposite end of the scale to represent 'Disagreed'. Because participants provided one single rating under each condition, this did not violate the statistical assumption of independence. The frequencies in which 'Agreed' or 'Disagreed' were reported for each of the three variables across the two ceiling fan conditions were analysed using the Cochran's Q test [57]. Since ratings of 'Neither agree nor disagree' represented a neutral state, evaluations made to this criterion were included in the analyses, but they did not influence the outcome.

To evaluate the differences, a two-fold approach was used. We compared the differences across the start and end of each session under the same ceiling fan; and also, the differences across different ceiling fans at both the start and end of the sessions. While the former approach sought to evaluate the differences in each subjective parameter following the completion of the three cognitive tasks, the latter analysis directly compared the evaluations across the ceiling fans at the points before and after these tasks were completed. To counterbalance the experiment-wise error rate (i.e., the significance level inflating across related pairwise comparisons), Bonferroni-Holms corrections were applied [58].

Directionality of the hypotheses (i.e., informing the test to examine either a positive, negative difference across the conditions) [59] were informed by our research aim. In other words, on the basis of the scientific literature, we believed that visual flicker caused by the opaque ceiling fan would have a greater – negative – influence on cognitive performance indicators and on the subjective evaluations given by our test participants. To test this influence, one-tailed hypotheses were utilised [60].

Since the tests rely on null hypothesis significance testing (NHST), which is dependent on both the size of the sample and magnitude of the effect [61], we placed more emphasis on the effect size indicators rather than focussing solely on the level of statistical significance. The effect size indicator in our study was the Pearson's, *r*, which could be calculated by making use of the test statistic from the respective inferential tests utilised. The Pearson's, *r* can be calculated for the three different tests considered, in which equation (3) was used for the *t*-test, (4) for the Wilcoxon signed-rank test [50], and (5) for the Cochran's *Q* test [62].

$$r = \sqrt{\frac{t^2}{t^2 \bullet df}} \tag{3}$$

$$r = \frac{Z_{Score}}{\sqrt{N}} \tag{4}$$

$$r = \sqrt{\frac{Q}{b(k-1)}} \tag{5}$$

Whereby: *t* and *df* are the test statistic and degrees of freedom from the *t*-test, Z_{score} and *N* are the test statistic and the number of observations from the Wilcoxon sign-rank test, and *Q*, *b* and *k* are the test statistic, number of participants, and groups from the Cochran's *Q* test. While the effect size proposed by Serlin *et al.* [62] in (4) is equal to the eta-squared, when this it square-rooted this produces the Pearson's, *r* [51].

The values of Pearson's, *r* range from -1 to +1, whereby larger values – regardless of the sign – indicate a stronger effect and the final interpretation is that the differences across the conditions are larger. To interpret the outcome of the effect sizes, we used the thresholds proposed by Ferguson [63], whereby thresholds for 'small', 'moderate' and 'strong' ($r \geq 0.20$, 0.50 and 0.80, respectively) are given. Effect sizes lower than the minimum recommendation ($r < 0.20$), do not represent any practically significant effect.

To plot our data, we made use of box and whisker plots that present both mean (circle) and median (M_{dn} – (line)) central tendencies, respectively. The whiskers extend from the upper (75th quartile (Q3)) and lower (25th quartile (Q1)) hinges. The upper whisker extends, from the hinge, no further than 1.5 multiplied by the difference between the upper and lower hinges (inter-quartile range (IQR)) to the largest value, whereas the lower whisker follows this same calculation process only to extend no further than the smallest value [64]. Any points beyond the whiskers are consider as outliners in the plot.

3. Results

3.1. Cognitive performance tests

Figure 5 presents the results of the cognitive performance tests for measures of accuracy (percentage incorrect and maximum correct) and rate of speed (total response time and longest response time). The results are organised according to the three cognitive performance tests, which were performed by test participants under both the opaque and

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transparent ceiling fan. Plots (a), (b) and (c) correspond to the Stroop-test, plots (d), (e) and (f) to the switcher-task, and (g) and (h) to the digit-span task, respectively.

These plots present the data as boxplots showing the comparison of the differences across the two ceiling fan conditions, which are expressed by the descriptive (mean difference (ΔM) and median difference (ΔM_{dn})) and inferential (the associated level of statistical significance (*p*-value) and the calculated effect size (*r*)) statistics. Plot (i) presents the maximum correct responses from the digit-span task. While this plot uses the same data as shown in plot (h), a histogram was used as a secondary method to present the information. On the y-axis, the frequency representing the cumulative number of participants is given. This shows the maximum of correct responses they were able to recall when performing the digit-span task under both ceiling fan conditions, which have been organised along the x-axis – from left to right in order of increasing magnitude. The dashed lines represent the mean average values for each ceiling fan condition.

The figure shows no notable differences in the graphical, descriptive or inferential statistics across the two ceiling fan conditions for the Stroop-test or switcher-task. That is, participants appeared to perform these two tests at the same rate of speed and with the same degree of accuracy under both ceiling fan conditions. Therefore, the analyses of cognitive performance demonstrated no statistically significant or practically relevant influence of visual flicker for these two tasks. For the digit-span task, we found higher levels of incorrect response under the opaque ceiling fan (plot (g)). This suggests that participants had made more mistakes compared to when they performed the same congitive visual task under the transparent ceiling fan condition. Participants also recalled more numerical values correctly (i.e., had a longer short-term memory span) when performing the digit-span under the transparent ceiling fan condition. Plot (i) shows there was a higher frequency of participants that were able to correctly recall large number of numerical values (i.e., eight and nine) under the transparent ceiling fan condition. Descriptive and inferential statistics in plots (g) and (h) confirmed that cognitive performance was higher under the transparent ceiling fan condition, whereby weakly significant and practically relevant (i.e. 'small' effect sizes) were found. These findings suggest that, increased levels of visual flicker had resulted in a small reduction of the performance in the digit-span test.

Since the order of conditions meant that participants may have noticed the change in the experimental design (i.e. a different ceiling fan) in the second session, the data was also analysed to evaluate the first session only using between-subjects tests [65,66]. The results of the first session (Appendix) generally showed similar findings when considering both sessions (i.e. all data), whereby the differences in plots (a) to (f) were not statistically significant. For the digit-span test, the difference in the first session for plot (h) was not statistically significant and the effect size was smaller, but in plot (g) the effect size was larger. Since plots (g) and (h) show similar trends (i.e., the sign of the differences were the same) to those found in Figure 5, the outcome of the statistical tests for the first session may have been influenced by a smaller available dataset used to support the analyses. Nevertheless, the results when considering the data from the first session only suggest that prior experience did not appear to have an influence within the experimental design.

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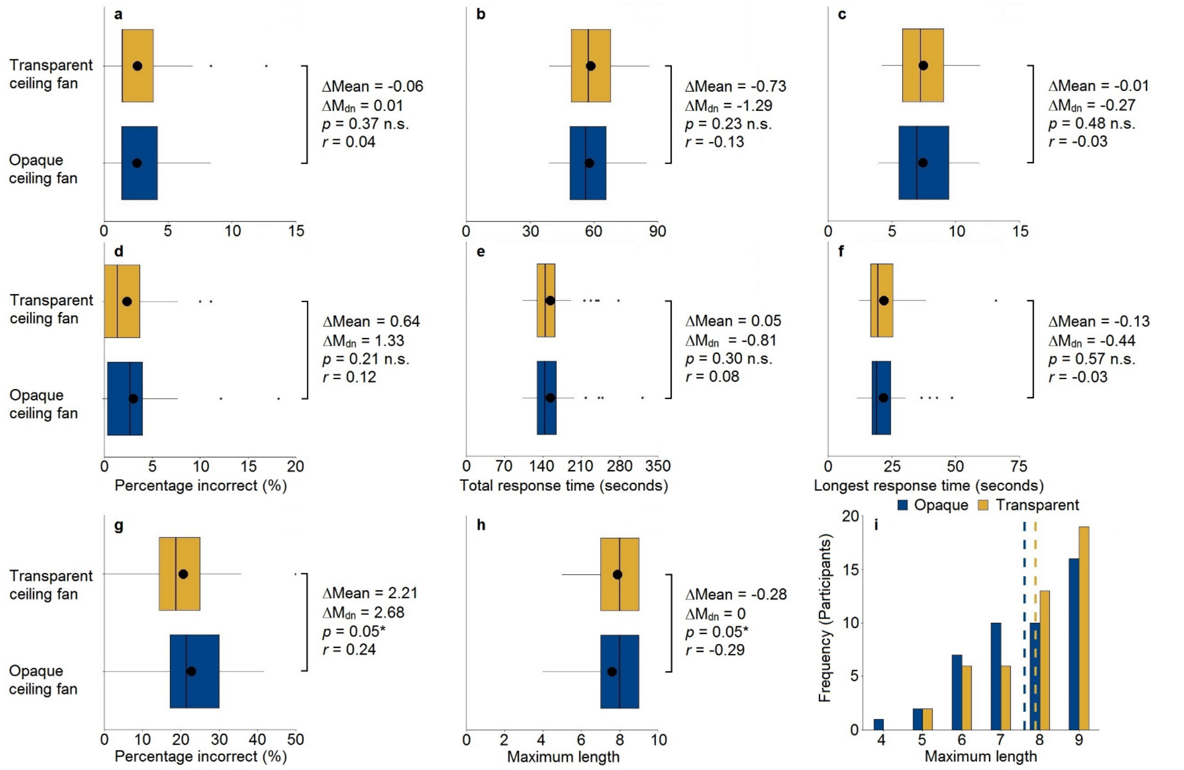

Figure 5. Boxplots presenting the results of the Stroop-test (a), (b) and (c), switcher-task (d), (e) and (f), and digit-span task (g) and (h). The plots present the measures of cognitive performance (percentage incorrect, total response time, longest response time, and maximum length (digit-span task only)) when the three tasks were performed under the opaque and transparent ceiling fans. The descriptive and inferential statistics are used to evaluate the difference in cognitive performance across the two conditions. Histogram showing the maximum length from the digit-span task (i). Note: data is the same as plot (h) and the dashed lines represent the mean average from each ceiling fan condition.

3.2. *Subjective evaluations*

Tables 2 and 3 report the descriptive and inferential statistics for the ten variables evaluated at the start and end of each test session under both ceiling fan conditions. Table 2 shows the mean and standard deviation (SD), M_{dn} and the IQR. Table 3 presents the ΔM_{dn} (as calculated from differences in Table 2) and associated statistical significance derived by the Wilcoxon signed-rank test, and the effect size (*r*).

The descriptive statistics (Table 2) show that participants generally gave low levels of ratings at the start and end of the test sessions under both ceiling fan conditions. This is noticeable for all variables presented in the table. The central tendencies for the ratings given ranged between the criteria 'Not at all' and 'Light' on the subjective scale.

Table 3 shows that five variables had differences that were statistically significant and practically relevant effect sizes when comparing the evaluations given at the start and end of the test sessions performing under the opaque ceiling fan condition. These variables and their associated effect size interpretation were: eye irritation (small), fatigue (small), sleepiness (small), difficulty concentrating (small), and difficulty thinking (small), respectively. For the transparent ceiling fan condition, three variables showed statistically significant and practically relevant effect sizes. These variables and their associated effect size interpretation were: eye irritation (small) and fatigue (small), and sleepiness (small), respectively.

Although participants reported elevated levels of fatigue and sleepiness after performing the three cognitive visual tasks, this was an expected consequence due to the mental effort required to perform these tasks. However, elevated levels of 'difficulty concentrating' and 'difficulty thinking' were only statistically significant and practically relevant when the differences were evaluated under the opaque ceiling fan. This finding may explain the reduction in cognitive performance found when participants had performed the digit-span task (i.e., because participants reported difficulty concentrating and thinking under the opaque ceiling fan condition, this reduced their ability to perform the cognitive tasks). This provides more supportive evidence that visual flicker may have influenced how participants both performed and reacted in the room containing the opaque ceiling fan. When comparing across the ceiling fans (opaque vs. transparent), no statistically significant and practically relevant differences were found.

Table 2. The results of the descriptive statistics for seven of the variables measured at the start and end when participants had completed the three cognitive visual tasks for both the opaque and transparent ceiling fans.

Variable[a]	*Opaque: Mean (SD)*	*Transparent: Mean (SD)*	*Opaque: M_{dn} (IQR)*	*Transparent: M_{dn} (IQR)*
Start of session				
Eye irritation	1.37 (0.65)	1.37 (0.61)	1 (1)	1 (1)
Headache	1.07 (0.25)	1.07 (0.25)	1 (0)	1 (0)
Dizziness	1.13 (0.40)	1.04 (0.21)	1 (0)	1 (0)
Fatigue	1.34 (0.60)	1.24 (0.48)	1 (1)	1 (0)
Sleepiness	1.52 (0.72)	1.44 (0.54)	1 (1)	1 (1)
Difficulty concentrating	1.44 (0.62)	1.35 (0.64)	1 (1)	1 (0.75)
Difficulty thinking	1.28 (0.54)	1.33 (0.60)	1 (0)	1 (0.75)

End of session				
Eye irritation	1.76 (0.92)	1.74 (0.86)	1.5 (1)	2 (1)
Headache	1.09 (0.29)	1.09 (0.29)	1 (0)	1 (0)
Dizziness	1.13 (0.34)	1.13 (0.40)	1 (0)	1 (0)
Fatigue	1.63 (0.77)	1.63 (0.71)	1 (1)	1.5 (1)
Sleepiness	1.78 (0.81)	1.70 (0.73)	2 (1)	2 (1)
Difficulty concentrating	1.70 (0.70)	1.50 (0.69)	2 (1)	1 (1)
Difficulty thinking	1.59 (0.72)	1.33 (0.60)	1 (1)	1 (0.75)

[a] 1= Not at all; 2= Light; 3= Moderate; 4= Strong; 5= Very strong; 6= Overwhelming

Table 3. The results of the Wilcoxon signed-rank test for seven of the variables. This presents the comparisons made across the start and end of each session under each ceiling fan, and the differences when directly considering the opaque and transparent ceiling fans at the start and end of each session.

Variable	Start vs. End: Opaque fan				Start vs. End: Transparent ceiling fan			
	ΔM_{ean}	ΔM_{dn}	*p-value*	*r*	ΔM_{ean}	ΔM_{dn}	*p-value*	*r*
Eye irritation	**-0.39**	**-0.5**	**0.00****	**-0.45**	**-0.37**	**-1**	**0.00****	**-0.46**
Headache	-0.02	0	0.28 n.s.	-0.09	-0.02	0	0.28 n.s.	-0.09
Dizziness	0	0	0.50 n.s.	0.00	*-0.09*	*0*	*0.05 n.s.*	*-0.24*
Fatigue	**-0.29**	**0**	**0.01***	**-0.37**	**-0.39**	**-0.5**	**0.01***	**-0.43**
Sleepiness	**-0.26**	**-1**	**0.01***	**-0.32**	**-0.26**	**-1**	**0.01***	**-0.36**
Difficulty concentrating	**-0.26**	**-1**	**0.01***	**-0.36**	*-0.15*	*0*	*0.08 n.s.*	*-0.21*
Difficulty thinking	**-0.31**	**-0**	**0.00****	**-0.45**	0	0	0.50 n.s.	0.00
Variable	**Opaque vs. Transparent: Start**				**Opaque vs. Transparent: End**			
	ΔM_{ean}	ΔM_{dn}	*p-value*	*r*	ΔM_{ean}	ΔM_{dn}	*p-value*	*r*
Eye irritation	0	0	0.55 n.s.	-0.02	0.02	-0.5	0.43 n.s.	0.03
Headache	0	0	0.50 n.s.	0.00	0	0	0.50 n.s.	0.00
Dizziness	0.09	0	0.10 n.s.	0.19	0	0	0.50 n.s.	0.00
Fatigue	0.10	0	0.13 n.s.	0.17	0	-0.5	0.53 n.s.	-0.01
Sleepiness	0.08	0	0.25 n.s.	0.10	0.08	0	0.32 n.s.	0.07
Difficulty concentrating	0.09	0	0.28 n.s.	0.09	0.20	1	0.13 n.s.	0.17
Difficulty thinking	-0.05	0	0.64 n.s.	-0.05	*0.26*	*0*	*0.04 n.s.*	*0.25*

Bold denotes comparisons that produced statistically significant and practically relevant differences
Italic denotes comparisons that produced practically relevant differences, but were not statistically significant
Bonferroni-Holms corrected: ***highly significant; **significant; *= weakly significant; n.s.= not significant
Effect size: r<0.20= negligible; 0.20≤r<0.50= small; 0.50≤r<0.80= moderate; r≥0.80= strong

A practically relevant difference was detected at the end of the session between ratings given to difficulty thinking, but this difference was not statistically significant. Dizziness under the transparent fan condition (start vs. end) was also practically relevant, but not statistically significant. However, for these comparisons, this was a consequence from the use of the Bonferroni-Holms correction (i.e., without adjusting the threshold in which the null hypothesis would have been rejected, statistical significance would have been declared).

For the variable headache, no comparisons in Table 3 showed statistical evidence to suggest that the rates across any of the conditions were different. This suggests that the influence of flicker did not have a notable effect on this parameter.

Figure 6 plots the frequencies (expressed by percentages) under both ceiling fan conditions for each criterion on the 5-point scales reported for the variables, air-movement, visual flicker, and blade movement, respectively. The aggregated criteria ‘Disagreed’ (D) and ‘Agreed’ (A) display the percentages that participants had reported either ‘Strongly disagree’ or ‘Disagree’ and ‘Agree’ or ‘Strongly agree’. The plots are separated by the evaluations made at the start (a, c and e) and end (b, d and f) of the test session for each variable and ceiling fan. The figure legend is coloured to represent ratings, whereby participants had either agreed (red) or disagreed (green) that the variable was uncomfortable.

Table 4 shows the results of the Cochran’s *Q* test to determine whether the differences between criteria of ‘Disagree’ and ‘Agree’ were statistically significant across the two ceiling fan conditions and the start and end of the test sessions.

Across the start and end of the test session, none of the comparisons in Table 4 were statistically significant, and only one difference was practically relevant. This was for the variable air-movement under the opaque ceiling fan. We had no reasons to believe from Figure 6 and Table 4 that, the ratings given to the variable air-movement were different across any of the comparisons considered. Therefore, we believe that the differences in air-velocities in Figure 4 did not have any unwanted influence on the experiment.

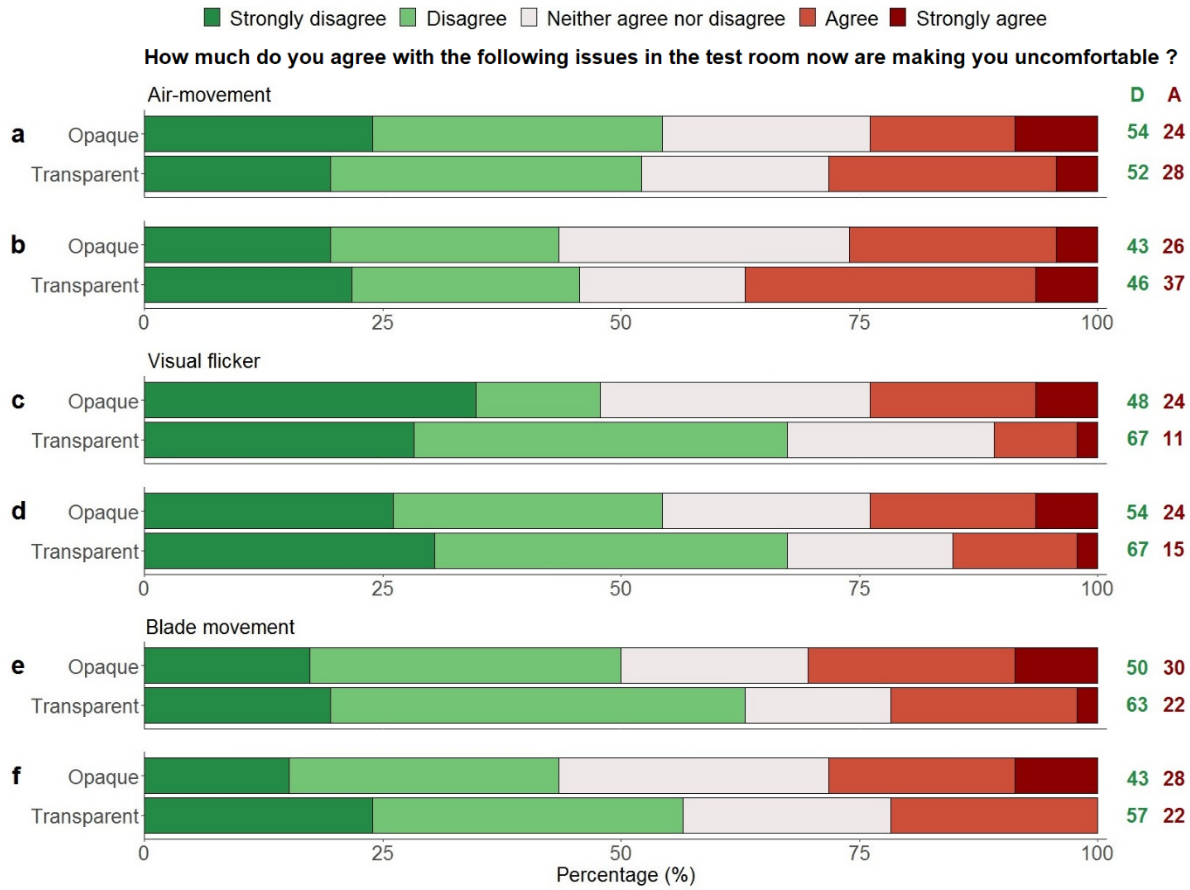

Figure 6. Plots showing the differences in the proportions for ratings given on the 5-points scales across the two ceiling fan conditions. The plots correspond to the ratings given at the start (a, c and e) and end (b, d and f) of each session for variables air-movement, visual flicker and blade movement. The values to the right of the scale represent the percentage of participants that disagreed ('D') or agreed ('A') that the variable caused discomfort.

Differences that were statistically significant were for comparisons made across the two ceiling fan conditions. Interestingly, this is the opposite of the statistical comparisons reported in Table 3. Figure 6 shows that participants disagreed more that, the variables visual flicker and blade movement were uncomfortable under the transparent ceiling fan. Conversely, more participants agreed that these same variables were uncomfortable under the opaque ceiling fan. Table 4 shows that all four comparisons (i.e. start and end and 'Disagreed' and 'Agreed') were practically relevant, and the differences were also statistically significant in two comparisons. Across these two conditions, this showed that participants 'Disagreed' more by 19 % at the start and by 13 % at the end of each test session that the transparent ceiling fan was uncomfortable due to visual flicker. However, the differences were not statistically significant for the criterion 'Agreed'.

The differences for the variable blade movement were practically relevant for the criterion 'Disagreed' but were not statistically significant. For the criterion 'Agreed' the differences were neither statistically significant nor practically relevant. Similar to Table 3, two differences in Table 4 were practically relevant, but not statistically significant due to the adjustment made by the Bonferroni-Holms correction. These were for the variables visual flicker ('Agreed' criterion) and blade movement ('Disagreed' criterion).

Table 4. The results of the Cochran's *Q* test for the three variables. This presents the comparisons made across the start and end of each session under each ceiling fan, and the differences when directly considering the opaque and transparent ceiling fans at the start and end of each session.

Start vs. End

Variable	**Fan**	**Disagreed**		**Agreed**	
		p-value	*Effect size (r)*	*p-value*	*Effect size (r)*
Air-movement	Opaque	*0.10 n.s.*	*0.24*	0.14 n.s.	-0.05
	Transparent	0.44 n.s.	0.11	0.21 n.s.	-0.18
Visual flicker[a]	Opaque	0.26 n.s.	-0.16	1.00 n.s.	0.00
	Transparent	1.00 n.s.	0.00	0.32 n.s.	-0.15
Blade movement[a]	Opaque	0.37 n.s.	0.13	0.76 n.s.	-0.04
	Transparent	0.69 n.s.	0.12	1.00 n.s.	0.00

Opaque vs. Transparent

Variable	**Session**	**Disagreed**		**Agreed**	
		p-value	*Effect size (r)*	*p-value*	*Effect size (r)*
Air-movement	Start	0.81 n.s.	0.04	0.53 n.s.	-0.09
	End	0.76 n.s.	-0.04	*0.13 n.s.*	*-0.22*
Visual flicker[a]	Start	**0.01***	**-0.37**	*0.03 n.s.*	*0.31*
	End	**0.05***	**-0.30**	0.10 n.s.	0.24
Blade movement[a]	Start	*0.16 n.s.*	*-0.21*	0.21 n.s.	0.19
	End	*0.05 n.s.*	*-0.28*	0.41 n.s.	0.13

Bold denotes comparisons that produced statistically significant and practically relevant differences
Italic denotes comparisons that produced practically relevant differences, but were not statistically significant
[a] Bonferroni-Holms corrected: ***highly significant; **significant; *= weakly significant; n.s.= not significant

4. Discussion

We designed an experiment to test the impact of visual flicker caused by an opaque and a transparent ceiling fan in two test-rooms. The results showed statistical evidence that an increased effect of visual flicker may have caused a small and just significant reduction in one out of three cognitive performances (digit-span task). Statistical significance could only be detected when using one-tailed hypothesis (i.e., when assuming elevated visual flickering could have only negative impact). If we would have used a two-tailed hypothesis (i.e., when assuming elevated visual flickering could have a positive or negative impact), there would not had been any statistical difference between any cognitive test. We think this finding needs to be highlighted because the working memory has an important role on everyday tasks. Working memory is vital when understanding details over time, whereby information is mentally held, processed and directed towards subsequent actions [67]. Therefore, working memory can have a crucial role on a range of tasks (e.g., speaking, writing, mathematics) that

https://doi.org/10.1016/j.buildenv.2020.107060
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occupants are regularly required to complete. While the effect on working memory appears to be small, its relevance within the larger context of the built environment could be much more substantive as it impacts many cognitive decisions.

A possible explanation for this result may have been the differences across the three tasks, which examine different aspects of cognitive performance. Working memory can have an important role when controlling for the impacts of external distractions on cognitive performance [68,69], whereby participants could have become distract due to the peripheral flicker caused by the fan and this hindered this ability recall the numerical information correctly.

While the experiment was setup to identify whether there was an effect of flicker within the peripheral visual field, the frequencies in which discomfort due to flicker was reported to be uncomfortable (Figure 6) were relatively low. Since the visual fixation of participants was focussed on the cognitive visual tasks, it is possible that the discomfort due to flicker may have been minimised as their attention was drawn away from the ceiling fans. Similar findings have been derived in our previous work [70]. Another possible reason may have been cultural. Since many participants were native to Singapore, there may have been some habitual effects that influenced the subjective evaluations. Across many building typologies in Singapore, ceiling fans are a typical method of creating convective cooling (Figures 1 and 2) but are installed without preventing visual flicker. Resultantly, occupants may have habituated to the discomfort that they cause over prolonged exposure periods.

Since flicker is known induce adverse symptoms, which include headaches and even epilepsy [13], populations that have a history of these – or similar – conditions were not included in our study. Across prevalence reports, it has been estimated that approximately 12 % of the populations studied suffer from migraines [71]. A recent report showed that in 2016, 8.2 % of the general population in Singapore had prevailing symptoms of migraines [72]. Since our work did not include this population, it would be important to understand the influence of flickering caused by ceiling fans with opaque or transparent blade on individuals that have a history of migraines.

Table 3 showed that most of the statistically significant difference found were from comparisons made across the start and end of the sessions, and not when directly comparing the evaluations between the two ceiling fans. Interestingly, under the opaque fan condition, higher levels of 'difficulty concentrating' and 'difficulty thinking' were reported across the test sessions. This same influence was not found under the transparent fan condition. This may, in part, have been caused by a moderating effect the cognitive tasks had with visual flicker produced across the two different ceiling fans. Nevertheless, important questions can be raised to determine if visual flicker is modulated by the type and level of difficulty of the task, as has been discovered in other areas of visual discomfort [73]. This would allow minimum recommendations to be established in different buildings that require occupants to perform different visual tasks.

We believe further work may also be needed to better understand the influence of exposure duration. Participants were exposed to visual flicker for a relatively short period (i.e., less than one hour in a test session). Hence, it is not clear whether exposure to the same conditions in our study would have been produced comparable results if a larger sample of participants were exposed for a whole working day period (e.g. eight hours).

4.1. Limitations and recommendations

Some limitations associated with our experimental methodology need to be acknowledged. Our methodology utilised two test-rooms containing different ceiling fans with participants undertaking the procedure under a crossover design to present both conditions. Although we equally balanced the order sequence in which participants completed both conditions, the change in the experiment setting (i.e. the ceiling fan) was always presented in the second session. However, when debriefing participants and revealing the true nature of the experiment [49], none of the participants reported that they were aware of the research aim or that effect of visual flicker was the primary focus of the experiment. Additional measures were also implement to help minimise this potential bias [74]: e.g., not mentioning any information that may give away the aim of our experiment on recruitment advertisements, consent forms, or procedural information.

We only considered fixed conditions (i.e., two ceiling fans with different MDs, but with constant rotational speeds (6.6 Hz)). Although these parameters are within the range of values known to cause adverse effects [16], a much wider range of conditions would give a better characterisation of the visual flicker caused by ceiling fans. Since the transparent ceiling fan still produced some degree of visual flicker (Table 1), one such condition may have been a 'no ceiling fan' case.

Retrospective of the findings in this study, we think some general recommendations can be derived to inform the design of ceiling fans in buildings. Our findings advocate the use of ceiling fans that minimise visual flicker. Although from the setup of our study this would promote transparent ceiling fans, this design has other potential risks. Due to the visual aliasing (e.g., wagon-wheel effect) created by the rotation speed, the blades of the transparent fan would be less visible than those of an opaque design and should not be used in spaces that have a low height restriction. In other words, a designer must mount the transparent ceiling fan at a height, whereby the occupants are not at risk of being in physical contact (e.g., when raising their arms upwards). Similar safety constraints are highlighted by the UL 507 standard [75] for ceiling fans mounted below 3.05 m from the floor.

In rooms where there is no obvious risk of causing physical harm to the occupants, we believe transparent fans are the preferred design that can offset the risks of visual flicker. For spaces that have low floor to ceiling constraints, designers may need to explore alternative solutions: e.g., bladeless ceiling fans, desk or wall fans.

5. Conclusions

We evaluated the influence of visual flicker from an opaque and a transparent ceiling fan in two controlled test-rooms. We found that, higher visual flicker produced by the opaque ceiling fan influenced the experimental results by:

(1) Compared to the ceiling fan with transparent blades, the opaque fan did not have an effect on cognitive performance measured with Stroop-test and switcher-task and a small and just significant reduction for the digit-span task.

(2) Visual flicker did not appear to influence any of the comparisons made across the two ceiling fan conditions for reported levels of eye irritation, headache, dizziness, fatigue, sleepiness, difficulty concentrating and difficulty thinking, respectively. However, participants reported higher levels of levels of difficulty concentrating and thinking across the test sessions under the opaque ceiling fan, but these elevated effects were not present under the transparent ceiling fan condition.

(3) Uncomfortable conditions caused by visual flicker were reported more frequently under the opaque ceiling fan in comparison to the transparent ceiling fan condition.

Although we think that visual flicker caused by the opaque fan have some adverse effects on the parameters measured in this study, it is important to highlight that the exposure length used was relatively short. Therefore, we do not yet know how the parameters measured are affected when a more representative exposure duration to that found in buildings containing ceiling fans is used. The issue of visual flicker should be addressed in the design and operation of indoor spaces with ceiling fans.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is funded by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a centre for intellectual excellence in research and education in Singapore. This research is carried out within the state of the art SinBerBEST Testbed (http://sinberbest.berkeley.edu/content-page/testbed-facilities) located in Singapore.

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Appendix

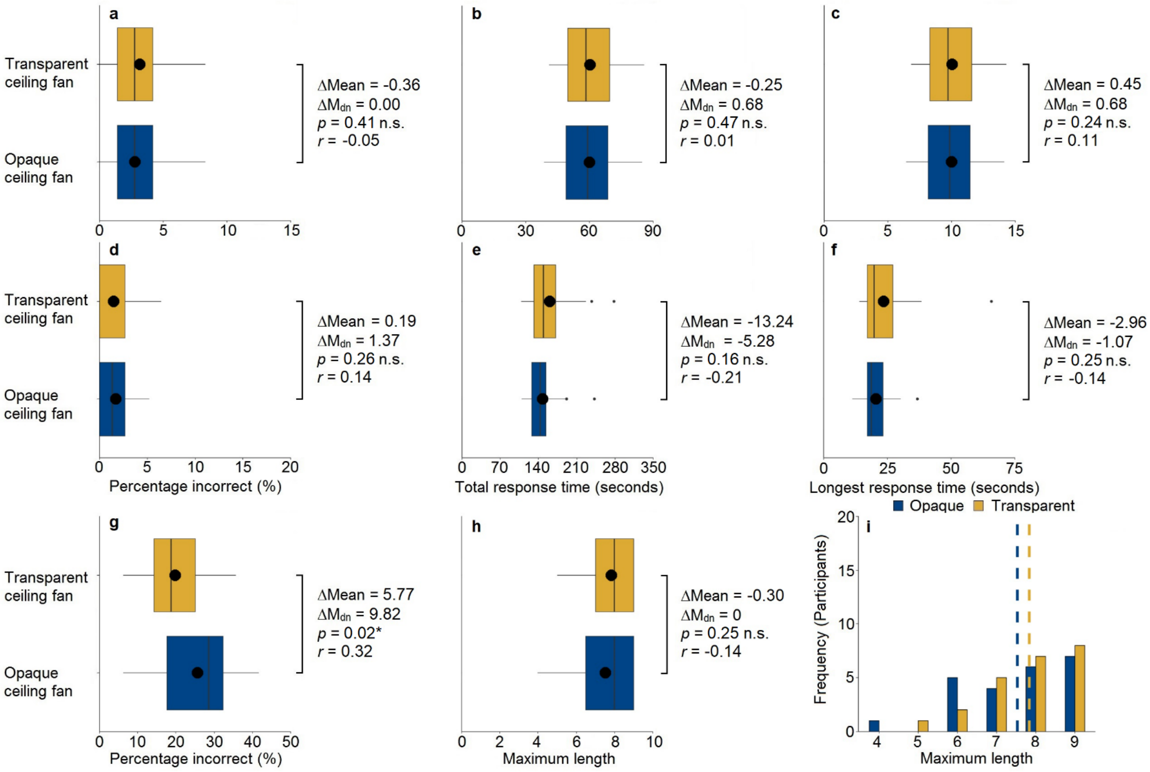

Figure A.1. Boxplots showing data from the first session only for the Stroop-test (a), (b) and (c), switcher-task (d), (e) and (f), and digit-span task (g) and (h). The plots present the percentage incorrect, total response time, longest response time, and maximum length (digit-span task only) when the three tasks were performed under the opaque and transparent ceiling fans. The descriptive and inferential statistics are used to evaluate the difference in cognitive performance across the two conditions. Histogram showing the maximum length from the digit-span task (i). Note: data is the same as plot (h) and the dashed lines represent the mean average from each ceiling fan condition.

https://doi.org/10.1016/j.buildenv.2020.107060
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