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A suitable and energy-efficient luminous environment for a shared office

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This paper aims to identify suitable and energy-efficient luminous environments for two users sharing the same office and conducting various activities at the same time (paper and/or computer-based work, meeting with a visitor). The office is lit by daylight, controlled by an exterior shading system and by artificial light, composed of ceiling sources and a task lamp on each desk. In all, 930 subjects participated in six psychophysical tests conducted on the internet, each dedicated to a user position and an activity. Multiobjective optimizations were then performed with the collected data in order to identify luminous environments that realized the best tradeoffs between visual conditions for both users and power demand. An optimized luminous environment, judged suitable, whatever the combinations of activities in the room, is proposed.

1. Introduction

The current energy situation requires that the power demand of office lighting is reduced. Yet, to ensure user satisfaction, the lighting design solutions should take into account user's needs and visual preferences. In the context of offices, those preferences about lighting quality may vary according to the conducted activity and the user position, as highlighted in previous work.[1–6]

First, Berrutto *et al.*[1] compared artificial lighting installations by collecting user's preferences according to different activities (paper-based work, computer-based work, meeting). In two individual experimental offices, panels of subjects adjusted luminous flux to obtain a suitable luminous environment for the activity, with or without a constraint on power density (<8 W/m^2). This study highlighted that adjusted luminous environments depend on the activity. Similarly, Yamakawa *et al.*[2] carried out psychovisual tests in which a panel of subjects set the luminous flux of a task lamp under three levels of ambient artificial lighting (200, 300 or 400 lx) to obtain luminous environments suitable to conduct various activities. For paper-based work (respectively computer-based work), illuminances provided by the task lamp ranged from 290 lx to 330 lx (respectively from 175 lx to 303 lx), according to the initial ambient illuminance. Similar findings were obtained in daylit offices.[3] According to surveys conducted in a French office building fitted with individual artificial

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light control, Escuyer and Fontoynont[4] found that the illuminances set by the users was lower for those mainly working on computers than the others. Similarly, Jennings *et al.*[5] showed that preferred light levels differ depending on the occupation: Light levels required by lawyers, working on paper, are higher than computer graphics designers, working on computers. Thus, previous work shows the lighting preferences are related to user activity in an office room.

Second, Laurentin *et al.*[6] interrogated a panel of subjects who had to adjust artificial lighting so as to obtain comfortable natural-artificial lighting to work on a computer at three different desks situated at various distance from the window. The adjustments varied according to the desk position. Moreover, the study results highlighted that the same user can work under various lighting conditions according to the distance of his desk to the window. Wang and Boubekri[7] studied ten work positions in a classroom for which the exterior view, the distance to sun patches on the ground, the sun exposure, the feelings of privacy and control varied. According to performance, cognitive and preference tests, subjects preferred to be situated close to the window even if their performance was not improved.

Thus, as lighting preferences are related to user's activity and position in an office room, Galasiu and Veitch[3] encouraged research about potential conflicts between different users of an office room where individual control is available and shading devices are semi-automatic or manual. The goal of this paper is to provide some insights to this question, by identifying solutions that realize some of the best feasible tradeoffs between visual satisfaction for all the users and reduction of power demand. For that purpose, we employ the multiobjective optimization method already applied in a pilot study.[8]

The method is divided into two steps: (1) psychovisual data acquisition and (2) integration of the psychovisual data into the multiobjective optimization process. An overview of the method is presented in Figure 1. The first step is dedicated to the acquisition of psychovisual data over the decision space (in which each potential solution to the multiobjective optimization problem is defined with a vector of decision variables). A psychovisual test is conducted to collect judgments on lighting solutions sampled over the decision space. Statistical analyses are employed to determine the average judgments of all participants. In the

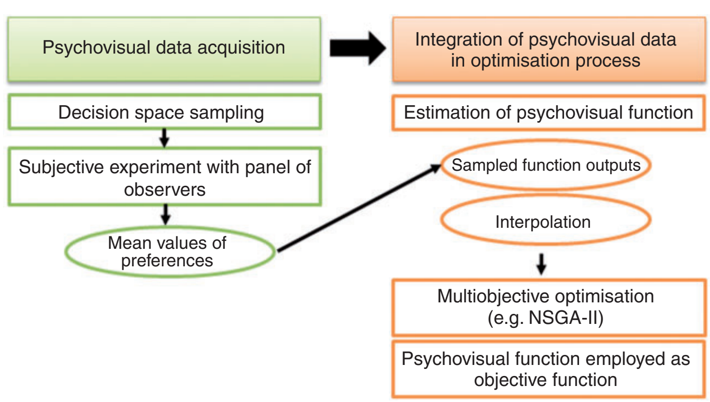


Figure 1 Overview of the proposed methodology

second step, psychovisual functions are estimated from the mean values obtained for each tested lighting solution and employed as objective functions (for each potential solution defined in decision space, the objective function quantifies its performance for the considered objective) in the optimization process to obtain an approximation of the Pareto Front, i.e. actually the set of the best feasible tradeoffs between conflicting objectives. The Pareto Front is estimated through evolutionary algorithms, such as NSGA-II[9] (Non-dominated Sorting Genetic Algorithm).

This method requires preference data collected from panels of subjects. For this purpose, psychovisual tests are carried out to collect preference data depending on the position of two users sharing an office, and on the activity they are conducting (paper-based work, computer-based work, meeting with a visitor). To collect data for each user and each activity, six psychovisual tests are needed. However, it is logistically difficult and time consuming to conduct so many psychovisual tests in a laboratory. In previous work,[10] by reproducing online a laboratory experiment, the use of the internet has been validated to collect judgments about the suitability of luminous environments represented through computer-generated images. Thus, the purpose of this paper is first to report the psychovisual tests conducted on the internet; the results of these tests are then used to build a database of user judgments about suitability of luminous environments in a shared office, lit by a combination of natural and artificial light. Second, multi-objective optimizations are carried out to contribute to answer the question raised by Galasiu and Veitch[3], by identifying suitable and energy-efficient luminous environments in shared office in which various activities are conducted.

The remainder of the paper is organized as follows. In Section 2, the developed case study is presented. In Section 3, the online-based psychovisual tests are described and their results are presented and commented on. In Section 4, results of the multiobjective optimizations carried out are detailed. Discussion relative to the findings is developed in Section 5. Section 6 concludes.

2. Case study

The case study used in this paper is an office room (representative of common European offices) shared by two users. The layout of the office room ($4.05\,m \times 5.70\,m \times 2.70\,m$) is presented in Figure 2. In order to distinguish

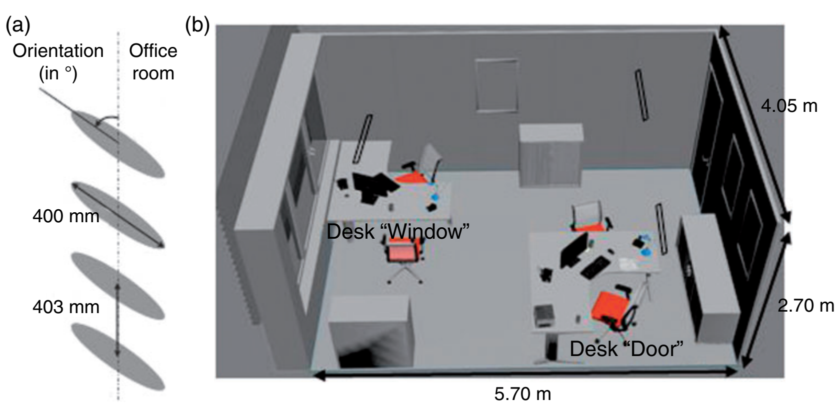


Figure 2 (a) Brise soleil shading device scheme (0° = vertical) (b) Double office layout

Table 1 Mean illuminances due to daylight

O_{Shad}	Window desk	Door desk
0°	15 lx	10 lx
45°	150 lx	50 lx
90°	200 lx	75 lx
150°	350 lx	130 lx

each user position, the desk close to the window (respectively to the door) will be mentioned as the 'Window Desk' (respectively 'Door Desk'). The room is lit by:

- Daylight through the office window (height: 1.9 m, width: 3.6 m, sill height: 0.7 m, glazing transmission coefficient: 0.9), with an external 400 mm elliptic brise soleil (Colt) (see Figure 2). Mean illuminances provided by daylight on the desks are reported in Table 1, depending on the shading device orientation;
- Three recessed luminaires with parabolic louvres. Each one contains a 1×28 W T5 fluorescent tube (4000 K, CRI = 80, 92.8 lm/W) and an electronic ballast. Each luminaire provides a maximum luminous flux of 2600 lm, so the total luminous flux is 7800 lm, providing 250 lx on the window desk and 490 lx on the door desk;
- On each desk, one angle-arm task lamp with a 1×11 W compact fluorescent lamp (CFL) (3000 K, CRI = 80, 81.8 lm/W). Each task lamp emits 900 lm providing, 490 lx on a desk.

Office reflectance values were chosen according to the European standard EN12464-1[11] and are: 0.7 for the ceiling, 0.7 for walls and 0.3 for the floor. The desktop colour is light wood.

The external brise soleil blinds are fixed outside the window and can only be tilted at different angles: 0° corresponds to a vertical position of the slats (the blind is closed), 90° corresponds to a horizontal position of the slats. The curved arrow in Figure 2(a) gives the direction of rotation from 0°.

Images representing the luminous environments to be assessed were computed by varying:

- The orientation (O_{Shad}) of the external brise soleil blinds (0°–150°) (defined in Figure 2(a));
- The amount of luminous flux (F_c) provided by the ceiling light sources (0–7800 lm);
- The state of the task lamps (switched on/off).

The sky type is limited to the standard CIE overcast sky (simulated according to overcast CIE sky[12]).

In order to collect subjective data about luminous environments represented on computer-generated images separately for each conducted activity, three points of view per desk were defined for: paper-based work (Paper), computer-based work (Computer) and meeting with a visitor (Meeting). Two user positions in the room were considered: working at the door desk or at the window desk. As a result, six setups (2 user position × 3 activities) have been defined (see Figure 3). The paper or the computer screen was not readable in all the lighting conditions, in order to avoid a bias due to visual acuity. The points of view follow the recommendations of European offices: For example, desks are perpendicular to the window to limit glare and reduce the maximum contrast in the field of view of the workers.[13,14] As a result, the luminaires cannot be seen and there is very little view of the windows in the stimuli.

3. Acquisition of psychovisual data

3.1. Psychovisual tests

For each setup (defined for a given desk, a given activity associated with one point of view), a psychovisual test was carried out with 48 stimuli. Figure 3 summarizes the six conducted psychovisual tests (from $\zeta 1$ to $\zeta 6$), where the 48 luminous environments were defined for assessment as follows:

- $O_{Shad} = 0°, 45°, 90°$ or $150°$;

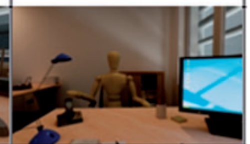
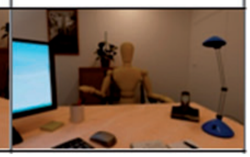
	ζ1	ζ2	ζ3
Sky type	Overcast	Overcast	Overcast
Desk	Window	Window	Window
Activity	Paper	Computer	Meeting
Example of stimulus			
	ζ4	ζ5	ζ6
Sky type	Overcast	Overcast	Overcast
Desk	Door	Door	Door
Activity	Paper	Computer	Meeting
Example of stimulus			

Figure 3 Six setups for the psychovisual tests

- F_c = 0%, 50% or 100% of maximum ceiling luminous flux;
- F_{Wind} = state of the task lamp switched on or off on the Window Desk;
- F_{Door} = state of the task lamp switched on or off on the Door Desk.

According to previous validation work,[10,15] psychovisual tests can be conducted on the internet with around 100 observers to remove bias due to uncontrolled conditions,[10] and can be built with balanced incomplete block experimental design to limit the duration of the experiment for each observer.[15] Thus, by employing a balanced incomplete block experimental design, each test required a panel of 282 subjects who judged 16 stimuli out of 48, each luminous environment being assessed 94 times (48*94 = 16*282). In total, 48*94*6 = 27,072 judgments of luminous environments were collected on the internet.

3.2. Panel

The characteristics of the six panels of 282 subjects who carried out the six psychovisual tests are presented in Table 2. The experimenter tried to obtain panel characteristics as similar as possible for each psychovisual test.

3.3. Protocol

For tests ζ1 and ζ4, observers were asked to imagine themselves ‘working on paper at the desk of the office’ and to rate randomly each image between 0 (not suitable at all) to 10 (extremely suitable) answering the question: ‘Is the luminous environment suitable to work on paper?’

For tests ζ2 and ζ5, observers were asked to imagine themselves ‘working on computer at the desk of the office’ and to rate randomly each image between 0 (not suitable at all) to 10 (extremely suitable) answering the question: ‘Is the luminous environment suitable to work on computer?’

Table 2 Panel characteristics for the six psychovisual tests

		$\zeta 1$	$\zeta 2$	$\zeta 3$	$\zeta 4$	$\zeta 5$	$\zeta 6$
Gender	Men	161	162	148	164	156	146
	Women	121	118	133	118	124	135
	NA	0	2	1	0	2	1
Age	18–34	184	174	194	177	177	199
	35–50	60	55	41	66	54	38
	51–66	37	45	39	37	45	37
	>66	1	6	7	2	4	7
	NA	0	2	1	0	2	1
Activity	Student	77	83	84	72	89	87
	Worker	184	179	174	193	176	171
	Retired	7	14	16	5	10	18
	NA	14	6	8	12	7	6
Corrected Vision	Yes	108	140	116	111	132	114
	No	160	134	158	160	142	160
	NA	14	8	8	11	8	8

For tests $\zeta 3$ and $\zeta 6$, observers were asked to imagine themselves ‘meeting with a visitor’ and to rate randomly each image between 0 (not suitable at all) to 10 (extremely suitable) answering the question: ‘Is the luminous environment suitable to conduct a meeting?’

3.4. Experimental conditions

The office scene was modeled with the 3DS MAX package. Renderings were computed with the light transport simulation program V-Ray. According to a previous study,[16] V-Ray produces images that cause the closest feeling regarding the luminous environment, to what would be felt in a real-world scene. Moreover, the validation of psychovisual tests on the internet was conducted with images produced with V-Ray.[10,15]

The experimental campaign lasted four months. Subjects could select the time they wanted to spend doing the experiment, and so some of them provided data for several psychovisual tests. In total, 930 subjects were involved in this experimental campaign.

3.5 Results

3.5.1. Cluster analysis and adjusted means

For each psychovisual test, a cluster analysis of data was conducted by using Clustering of Incomplete Preferences CLIP method.[17] Outliers were identified for $\zeta 1$ and $\zeta 3$ tests but no existence of various groups with different judgments was highlighted. Then, a non-orthogonal Analysis of Variance (ANOVA)[18] was employed to take into account the use of incomplete block design and to determine adjusted mean values. Figure 4 presents the adjusted mean values and the associated 95% confidence interval (95CI) of each stimulus, according to the user position and user activity.

3.5.2. Do preferred luminous environments differ with activity and user position?

A multivariate analysis of variance (in General Linear Model (GLM) framework[17]) with four factors ‘Stimulus’ (48 modalities), ‘Block’ (282 modalities), ‘Activity’ (three modalities: Paper, Computer and Meeting) and ‘Position’ (two modalities: Window or Door) was conducted with STATISTICA. Table 3 presents the results. According to the Cohen definition,[19] a small effect corresponds to $0.01 \leq \eta_{\text{partial}}^2 < 0.06$, a medium effect to $0.06 \leq \eta_{\text{partial}}^2 < 0.14$ and a strong effect to $\eta_{\text{partial}}^2 \geq 0.14$.

According to Table 3, there is a significant small effect of the conducted ‘Activity’

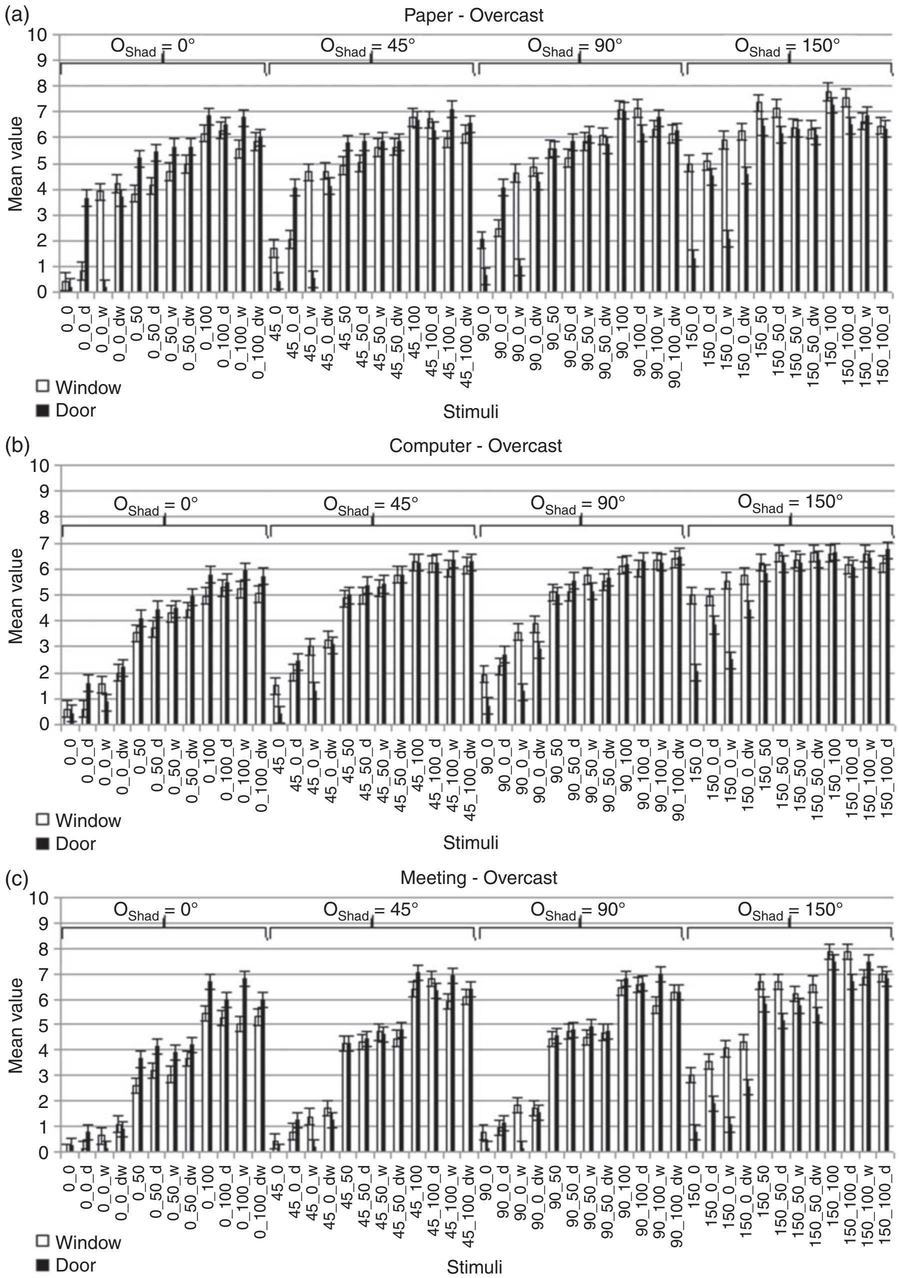


Figure 4 Adjusted mean values (a) paper-based work (b) computer-based work (c) meeting with a visitor (Horizontal axis - Name of Stimuli: O_{Shad}_F_c_state task lamp (*d* if $F_{Door} = $ on, *w* if $F_{Wind} = $ on), e.g. [90_100_d]: $O_{Shad} = 90^{\circ}$, $F_c = 100\%$, $F_{Door} = $ on, $F_{Wind} = $ off)

Table 3. ANOVA results

	Sum of squares	df	F	*p* Value	η^2-partial
Total	537,647	1			
Activity	1212	2	151.5	<0.0001	0.011
Position	141	1	35.37	<0.0001	0.001
Stimulus	109,532	47	582.58	<0.0001	0.506
Block	12,662	281	11.26	<0.0001	0.106
Activity*Position	1259	2	157.34	<0.0001	0.012
Error	106,959	26,738			

Table 4. *Post-hoc* test results conducted on the interaction 'Activity by Position'

Position	Activity	Mean ratings	Classes of Tukey *post-hoc*			
Door	Meeting	4.10	A			
Window	Meeting	4.21	A			
Window	Paper	4.21	A			
Door	Computer	4.52		B		
Window	Computer	4.73			C	
Door	Paper	4.96				D

($\eta_{partial}{}^2 = 0.011$) and of the interaction 'Activity × Position' ($\eta_{partial}{}^2 = 0.012$) on the suitability judgments although the significant effects of 'Activity' and of the interaction 'Activity × Position' are closed to the lower bound of the range of small effect sizes. These results mean that the luminous environments are differently judged depending on the conducted activity and the position of the user in the office. To go further, a Tukey *post-hoc* test[19] was conducted on the interaction 'Activity × Position' modalities. Results are presented in Table 4. Suitability judgments are significantly different between the users when they are conducting paper-based work or computer-based work. This result is consistent with previous research,[1,2,4,5] in which luminous environments identified as suitable for paper-based work are brighter than for computer-based work. Moreover, the effect of the position is consistent with the findings of Laurentin *et al.*[6]

However, according to adjusted mean values illustrated in Figure 4, opening shading devices to 150° and providing 100% of the ceiling luminous flux (the tasks lamps being switched off) make it possible to satisfy both users for any activities (Paper Door 7.2/10, Paper Window 7.8/10, Computer Door 6.7/10, Computer Window 6.6/10, Meeting Door 7.4/10, Meeting Window 7.9/10). This solution provides 600 lx on the task area for both users, with 300 lx (respectively 500 lx) coming from artificial lighting close to the window (respectively close to the door). These levels of illuminance are consistent with previous work conducted on a French panel.[4,6] However, even if both users are satisfied, this solution requires a high power demand (3.64 W/m^2). This result confirms the relevance of looking for the best tradeoffs between power demand and satisfaction of both users. For this purpose, a multiobjective optimization algorithm will be used in Section 4.

3.6 Conclusions

Psychovisual experiments about suitable luminous environments in an office shared by two users were conducted on the internet to study the influence of the user activity and position. In order to allow others to make use of the collected data, a database (including test results, panel characteristics, illuminance maps, HDR and LDR images) is available on a Dropbox account (login: celine.villa@entpe.fr password: lighting).

The findings suggest that there is a significant difference between preferences according to user position or conducted activity under an overcast sky. However, the most suitable luminous environments for both users whatever their activities are obtained with the maximum artificial lighting complement that maximizes the required power demand. Thus, in the following section, a multiobjective optimization algorithm is employed using the collected data in order to identify the best tradeoffs to satisfy both users and to reduce power demand.

4. Identification of optimal tradeoffs

4.1. Estimation of psychovisual functions

For each user position (Window or Door) and for each activity (Paper, Computer or Meeting), a psychovisual function was estimated throughout the decision space with a bilinear interpolation based on the adjusted mean values of the 48 assessed luminous environments. These psychovisual functions can then be employed as objective functions in multiobjective optimization problems.

4.2 Multiobjective optimization results

4.2.1. Meeting a visitor

If the users are both conducting a meeting, the goal is to identify luminous environments that make it possible to ensure suitable lighting conditions for both users in their task and limit the power demand. It can be defined as a three-objective optimization problem with the three following functions in objective space:

– f_1: the power demand, in Watts, computed according to equation 1

$$f_3 = \left(F_c \times 84\right) + \left(F_{wind} \times 11\right) + \left(F_{Door} \times 11\right) \tag{1}$$

– f_2: the opposite of the psychovisual function 'suitable' (Meeting, Window);

– f_3: the opposite of the psychovisual function 'suitable' (Meeting, Door).

To solve the multiobjective optimization problem, the genetic algorithm (GA) NSGA-II (Non-dominated Sorting Genetic Algorithm) was employed. GAs search for the global minimum of functions; the maximum of the psychovisual function (=the most suitable) corresponds to the minimum of its opposite function. NSGA-II was developed by Deb *et al.*[9] with $O(mN^2)$ computational complexity (where N is the population size and m the number of objectives). Individuals are sorted according to non-domination ranking and crowding distance. The selection is conducted through a binary tournament by first comparing the non-domination rank and then the crowding distance. A simulated binary crossover (SBX) operator and polynomial mutation are employed. NSGA-II Matlab code is available online, and was employed together with the real-coded GA. Each gene corresponds to one decision variable. The population size and the number of generations were determined after numerical experiments to ensure convergence for each optimization problem. In this optimization, the genetic algorithm NSGA-II was employed with 400 individuals and 200 generations. The crossover rate was fixed at 0.9, the mutation rate at 0.5, the crossover distribution index[20] at $\eta_c = 20$ and the mutation distribution index at $\eta_m = 20$. The size of the mating pool was fixed at half of the population size (pool size = 200).

The result of the optimization carried out with the GA is an approximation of the Pareto Front in three-dimensional objective space. The Pareto Front presents the best tradeoffs that can be achieved between suitability of luminous environments for both users and power demand. The projection of the Pareto Front approximation in the (f_2,f_3) space is presented in Figure 5. A grayscale graphic code highlights the power demand level of each tradeoff.

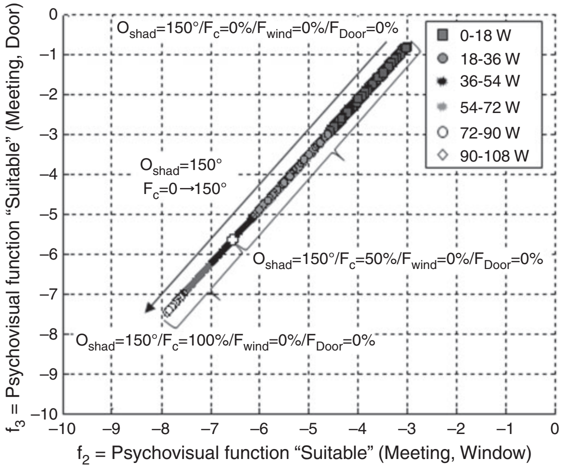


Figure 5 Results of the multiobjective optimization of f_1 (Power demand), f_2 (Meeting, Window) and f_3 (Meeting, Door): projection of the Pareto Front approximation in (f_2,f_3) space

Each tradeoff is achieved by a Pareto-optimal solution, defined with an orientation (O_{Shad}) of the external brise soleil (between 0° and 150°), the percentage of luminous flux (F_c) provided by ceiling light sources (between 0 and 100%) and the state of the task lamps (switched on or off). To limit the number of figures, the definition of Pareto-optimal solutions related to each tradeoff is written in Figure 5.

As no significant differences of judgment was obtained (Table 4) between both users conducting a meeting, the shape of the Pareto Front approximation is linear. According to Figure 5, the set of the best tradeoffs are achieved with a 150° orientation (O_{Shad}) of the external brise soleil and switched-off task lamps. Figure 5 is relevant with the results obtained in Section 3: Improving the preferences of both users makes it necessary to increase the amount of ceiling luminous flux, which results in higher power demand. It can be noticed that the Pareto Front approximation can be divided in two parts. The first part (gray squares and gray circles, from 0 to 36 W) corresponds to a high improvement of the preferences for a small increase of power demand, whereas the second part (black asterisks, gray asterisks, white circles, white diamonds, from 36 W to 108 W) indicates that from a given level of ceiling luminous flux, a high increase of power demand is required to slightly improve the visual conditions. Thus, an optimal solution that can be recorded would be the one that makes it possible to achieve the tradeoff at the edge of these two parts of the Pareto Front approximation defined with ($O_{Shad} = 150°$, $F_c = 50\%$, $F_{Wind} = 0\%$, $F_{Door} = 0\%$) requiring a power demand of 42 W (see the white cross in Figure 5). Performances of this solution are presented in Table 5.

This solution ensures a mean horizontal illuminance in the task area on the desk close to the window (respectively close to the door) of around 425 lx (respectively around 380 lx). The mean vertical illuminance on the wall in front of the user close to the window (respectively close to the door) is 525 lx (respectively 225 lx). The luminances of the wall in front of the user is on average 1.7 times higher (respectively 2.2 times higher) than the luminances on the model head close to the window (respectively close to the door), which is less than the maximum recommended 1:3 ratio.[21]

4.2.2. Paper-based work

If the users are both doing paper-based work, the multiobjective optimization problem can be defined with the three following functions in objective space:

- f_1: the power demand, in Watts, computed according to Equation (1);
- f_4: the opposite of the psychovisual function 'suitable' (Paper, Window);
- f_5: the opposite of the psychovisual function 'suitable' (Paper, Door).

The same settings as previously of the genetic algorithm NSGA-II was employed (400 individuals, 200 generations, crossover rate = 0.9, mutation rate = 0.5, $\eta_c = 20$, $\eta_m = 20$, Pool size = 200). Figure 6 presents the projection of

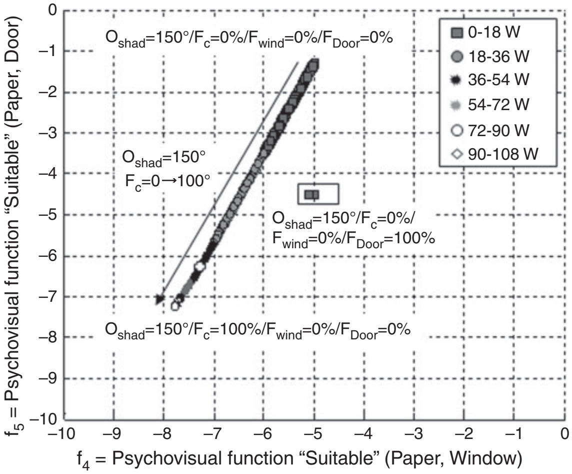
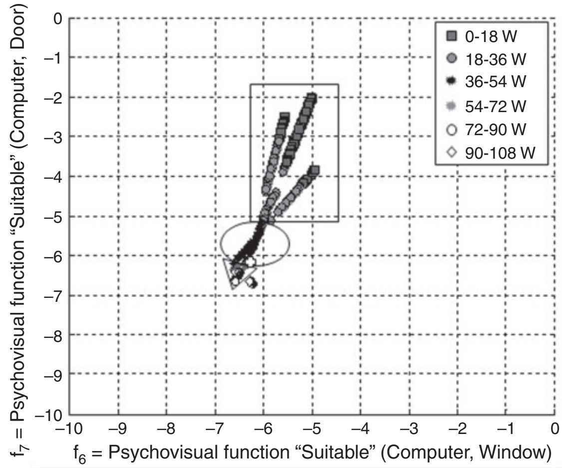


Figure 6 Results of the multiobjective optimization of f_1 (Power demand), f_4 (Paper, Window), f_5 (Paper, Door): projection of the Pareto Front approximation in (f_4,f_5) space.



Group	O_{shad}	F_c	F_{wind}	F_{Door}
G1	150°	0-20%	OFF or ON	OFF or ON
G2	150°	40-60%	OFF or ON	OFF or ON
G3	150°	90-100%	OFF	OFF if F_{wind} OFF
			ON	ON if F_{wind} ON
G4	150°	100°	ON	OFF

Figure 7 Results of the multiobjective optimization of f_1 (Power demand), f_6 (Computer, Window), f_7 (Computer, Door): projection of the Pareto Front approximation in (f_6,f_7) space

the Pareto Front approximation in the (f_4,f_5) space. The grayscale code defines the power demand level of each tradeoff. Most of the best tradeoffs are achieved with a 150° orientation (O_{Shad}) of the external brise soleil, switched-off task lamps and an amount of ceiling luminous flux between 0 and 100%. A subset of the best tradeoffs is also achieved with external brise soleil at 150°, 0% of ceiling luminous flux and the task lamp switched on, on the desk close to the door. Thus, according to the optimization results, setting the external brise soleil to 150° makes it possible to improve the lighting condition of both users whatever their position to work on paper. Besides, the shape of the Pareto Front is similar to the one obtained in Section 4.2.1. when users are conducting a meeting with a visitor. The same optimal solution ($O_{Shad}=150°$, $F_c=50\%$, $F_{Wind}=0\%$, $F_{Door}=0\%$) is recorded for the paper-based work (see the white cross in Figure 6).

4.2.3. Computer-based work

If the users are working on a computer, the goal is to identify luminous environments that make it possible to ensure suitable lighting conditions for both users in their computer task and limit the power demand. It can be defined with a three-objective optimization problem with the three following functions in objective space:

– f_1: the power demand, in Watts, computed according to Equation (1);
– f_6: the opposite of the psychovisual function ‘suitable’ (Computer, Window);
– f_7: the opposite of the psychovisual function ‘suitable’ (Computer, Door).

The same settings of NSGA-II was employed (400 individuals, 200 generations, crossover rate = 0.9, mutation rate = 0.5, $\eta_c=20$, $\eta_m=20$, Pool size = 200). The results of the optimization are presented in Figure 7. The projection of the Pareto Front approximation in the (f_6,f_7) space is displayed in Figure 7, in which the grayscale code indicates the power

Table 5 Performances of the recorded optimal solution ($O_{Shad} = 150°$, $F_c = 50\%$, $F_{Wind} = 0\%$, $F_{Door} = 0\%$) and luminance ratios

Performances	Luminance ratio
Power demand $f_1 = 42.00$ W	
-Psychovisual function 'suitable' (Meeting, Window) $f_2 = -6.69/10$	$L_{visitor}/L_{wall} = 0.42–0.77$ (>1:3)
-Psychovisual function 'suitable' (Meeting, Door) $f_3 = -5.82/10$	$L_{visitor}/L_{wall} \approx 0.46$ (>1:3)
-Psychovisual function 'suitable' (Paper, Window) $f_4 = -7.34/10$	$L_{paper}/L_{desk} = 1.12–1.16$ (~1:1)
-Psychovisual function 'suitable' (Paper, Door) $f_5 = -6.42/10$	$L_{paper}/L_{desk} \approx 1.15$ (~1:1)
-Psychovisual function 'suitable' (Computer, Window) $f_6 = -6.23/10$	$L_{screen}/L_{wall} \approx 1.74–2.19$ (<3:1)
-Psychovisual function 'suitable' (Computer, Door) $f_7 = -6.25/10$	$L_{screen}/L_{wall} \approx 1.64–3.30$ (≤3:1)

demand level. The best tradeoffs are achieved with an orientation (O_{Shad}) of the external brise soleil of 150° with:

- a low amount of ceiling luminous flux (0%–20%) whatever the state of the task lamps (group 1);
- a medium amount of ceiling luminous flux (40%–60%) whatever the state of the task lamps (group 2);
- a high amount of ceiling luminous flux (90%–100%) with the task lamps set in the same state (both switched off or both switched on) (group 3);
- the maximum amount of ceiling luminous flux (100%) with the task lamp close to the window switched on (group 4).

Optimal solutions belonging to group 1 (defined above) presents low power demand (<36 W) but are judged under 6/10 by both users (see rectangle in Figure 7), with especially low suitability level for the user close to the door. Power demand required by optimal solutions of group 2 is medium (<72 W) while presenting a level of suitability between 6 and 7/10 (respectively between 5 and 6.25/10) for the user close to the window (respectively close to the door) (see oval in Figure 7). Then, lighting solutions of group 3 and group 4 make it possible to ensure a suitability level between 6 and 7/10 for both users at the cost of a relatively high power demand (>72 W).

If an optimal solution had to be recorded, it would be the one of group 2 that ensures a suitability level over 6/10 for both users with a power demand under 2 W/m^2. The optimal solution ($O_{Shad} = 150°$, $F_c = 50\%$, $F_{Wind} = 0\%$, $F_{Door} = 0\%$) respects these constrained performances (see Table 5 and the white cross in Figure 7).

4.2.4. Others combinations of activities

In previous sections, multiobjective optimizations were conducted in order to identify optimal luminous environments if both users are conducting the same activity. Findings highlighted that in all the cases, the orientation (O_{Shad}) of the external brise soleil of 150° is optimal with an amount of ceiling luminous flux between 0 and 100%, and setting it to 50% ensures visual conditions with more than a 6/10 suitability rating together with a power demand under 2 W/m^2.

Similarly to the optimization problems detailed in Sections 4.2.1., 4.2.2. or 4.2.3., all combinations of activities conducted by the users were investigated through multiobjective optimizations: the optimization problems took into account that each user can conduct from one to up to three activities at the same time (e.g. [User door: meeting + computer, User Window: paper], [User door: computer, User Window: paper + computer + meeting], etc.). Thus, optimizations with up to seven objectives (power demand and up to six preference related objectives) were performed. Whatever the activities conducted by the users, optimal luminous environments making it possible to ensure suitable visual conditions to both users whatever their activity while limiting the power demand are obtained by setting the external brise soleil to direct the daylight towards the ceiling (150°). To limit the power demand under $2\,W/m^2$ and ensure a suitability level over 6/10 for both users, the same optimal solution ($O_{Shad} = 150°$, $F_c = 50\%$, $F_{Wind} = 0\%$, $F_{Door} = 0\%$) can be recorded for users conducting one, two or three activities at the same time, whatever the activity.

5. Discussion

5.1. Relevance and limits of multiobjective optimization

An optimal solution ($O_{Shad} = 150°$, $F_c = 50\%$, $F_{Wind} = 0\%$, $F_{Door} = 0\%$) was derived from the results of the multiobjective optimizations carried out, whatever the user position and the conducted activity. Respectively, 425 lx and 380 lx are provided on average in the task area on the desk close to the window and to the door. These are less than the recommendations for office lighting of the European Standard EN12464-1[11] (500 lx) or of the Illuminating Engineering Society of North America (50 Fc)[21] but consistent with the usual levels employed in French offices.[4] This solution is suitable for the users, and requires 1.82 W/m^2. This is half of the power demand required by the solution suggested from the direct analysis of the raw results (Section 3) of the psychovisual tests ($O_{Shad} = 150°$, $F_c = 100\%$, $F_{Wind} = 0\%$, $F_{Door} = 0\%$) and 84.6% less than the usual lighting power density provided in such offices (1.1 W/ft^2 required by IESNA[21], i.e. 11.8 W/m^2). This highlights the value of multiobjective optimization for lighting design.

The 150° orientation can limit the outside view, which is an important aspect to take into account in offices.[3,7,22] Therefore, other objectives could be taken into account also, such as the outside view preferences and the visual comfort of the meeting participants. Yet, the current study is quite close to the limits of the used methodology, since multiobjective optimization methods can hardly be applied when the number of objectives is too large.[23] In such cases indeed, the results of the optimization are difficult to interpret; graphical tools should be used to help the analyses but are still to be designed. Moreover, when the number of decision variables increases, the assessment of the psychovisual functions becomes difficult in practice, even when using advanced tools such as balanced incomplete block design and internet-based assessments. Indeed, the number of needed participants becomes too high when the number of decision variables is beyond eight.[24] Thus, the relevant decision variables and objectives should be carefully chosen before the study.

5.2 Effect of task lamp

In the identified optimal solution, the task lamps are switched off. Supplying an individual control of light is appreciated but it can lead to potential conflicts in a shared office.[3] Thus, this section analyses further the impact of the task lamps and focuses on the effect they can induce to ensure suitable and energy-efficient luminous environments for both users.

First, it should be noted that the task lamps do not have a high power demand (11 W each) with respect to the maximum power demand of the whole lighting installation (106 W): As a matter of fact, if the task lamps do improve the visual comfort of users, they could be switched on without having a dramatic impact on the energy efficiency of the installation.

For a given desk, there are no significant differences between mean values of preferences obtained when task lamp is switched on or off on the opposite desk (see the 95% confidence intervals in Figure 4). Thus, it seems that individual control with a task lamp in a shared office does not modify the lighting quality for other users. However, according to Figure 4, the higher the ceiling luminous flux is, the less necessary the task lamps are to ensure suitable luminous environments, especially to conduct paper-based work or a meeting. This is confirmed by the optimal luminous environments, which are defined with switched-off task lamps in Figures 5 and 6. For the computer-based task, since a subset of optimal solutions (Figure 7) is defined with switched-on task lamps, they do improve the visual conditions enough to consider increasing the power demand. Moreover, according to Figure 7, the visual conditions of one user are improved by switching on the task lamp on the desk of the other user when working on computer (see the examples of group 4 or group 1 in Figure 7). For example, for the user close to the window, one of the most suitable optimal solutions is obtained by providing between 40% and 50% of ceiling luminous flux and switching on the task lamp on the desk close to the door. The latter is not directly visible by the user close to the window in the tested point of view, but makes it possible to decrease the luminance ratio between the screen and the vertical wall in his field of view (for $F_c = 50\%$, the ratio of 1.73 becomes 1.69 with the switched-on task lamp on the desk close to the door). The same trend can be noticed for the user close to the door with the task lamp switched on, on the desk close to the window. For $F_c = 50\%$, luminances of the wall in the field of view of this user are on average 3.3 times higher than the screen luminances when the task lamp is switched off on the next desk, whereas they are 2.8 times higher when the task lamp is switched on. These comments are positive for the use of task lamps in a shared office in which computer-based work is the main activity. According to these results, the use of task lamp on a desk would have a positive effect on the visual conditions of the workmate. However, these findings are obtained from psychovisual tests conducted on images in which the user did not have a direct view of the task lamp source. Otherwise, discomfort glare could be induced by the task lamp of the workmate. This aspect should be investigated in future work.

6. Conclusions

The paper investigates if it is possible to identify luminous environments suitable for two users sharing the same office and conducting various activities (paper-based, computer-based, meeting with a visitor) with limited power demand. For that purpose, six psychovisual tests have been conducted on the internet with 930 subjects. Luminous environments in the office were assessed depending on the user position and on the conducted activity. The office was lit by daylight under an overcast sky, controlled by an exterior shading system and by artificial light, composed of ceiling sources and a task lamp on each desk. Results of the psychovisual tests showed that a specific installation (the shading system oriented at 150° to direct the daylight towards the ceiling, the luminous flux of the ceiling light sources set to 100%, the task lamps switched off) is suitable for users regardless of their positions and the conducted activities; yet, this lighting installation is power-demanding ($3.64\,W/m^2$). Multiobjective optimizations were then performed with the collected data. Sets of optimal luminous environments that realized the best tradeoffs between power demand and visual conditions of both users were identified for all the possible combinations of activities. The analyses of the multiobjective optimization results led to the identification of a single luminous environment (the shading system oriented at 150° to direct the daylight towards the ceiling, the luminous flux of the ceiling sources set to 50%, the task lamps switched off) that divided the power demand in half ($1.82\,W/m^2$) while maintaining suitable visual conditions, whatever the user position and the conducted activities. This result emphasizes the value and relevance of multiobjective optimization techniques, since it could not have been obtained directly from the raw data derived from the psychovisual tests. In addition, statistical and optimization analyses suggest individual control with the task lamp do not impact lighting quality for the other user in the room neither does it increase the power demand dramatically, and can have a positive impact in shared offices in which users are working on computer. Future work will investigate when the sky is sunny with the potential presence of discomfort glare.

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