307; Passive design for urban thermal comfort: a comparison between different urban forms in Cairo, Egypt

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Abstract

In order to achieve outdoor thermal comfort in hot, arid zones it is necessary to have a clear understanding of the interactions between the prevailing climate and the urban form. Modern urban planning in Cairo does not use the vernacular urban principles or architectural forms, choosing instead a hybrid urban form between the Arab vernacular compact urban architecture and the western suburban dot pattern urban form could enhance the situation. This study investigated the microclimatic thermal behaviour of hybrid traditional and modern street canyon types of urban form in Cairo in order to establish an urban planning tool for passive cooling. Numerical simulations were performed, using both thermal and CFD software, for a hot summer's day in Cairo for different street canyon configurations including different canyon orientations to the prevailing wind and different canyon geometries. Initial results indicate that very dense urban layouts can have a beneficial impact upon outdoor thermal comfort but can, if incorrectly orientated, severely reduce the potential for any wind-driven cooling because of excessive wind sheltering. Some urban layout combinations of canyon geometry and orientation are suggested to provide satisfactory outdoor thermal comfort conditions at street level.

Keywords: urban planning, thermal comfort, ENVI-met, Cairo

1. Introduction

Urban planning can have a significant impact upon the thermal microclimate experienced in outdoor spaces. As urban populations and urban developments continue to grow, a planning strategy that attempts to improve outdoor thermal comfort has several benefits. Firstly, upward temperature trends due to climate change will need to be ameliorated to allow people to move around urban areas. Secondly, a cooler outside will help lessen the thermal stress on internal building conditions. Finally, a cooler city centre will help reduce urban heat island (UHI) effects at a city and regional level. Urban thermal microclimates are characterised in terms of wind speed and direction, mean radiant temperature, air temperature and relative humidity [1]. The key planning parameters influencing this microclimate are building fabric and density, street canyon geometry and orientation [2,3,4,5]. In hot, dry climates, these elements must be planned to avoid excessive heat stress. Moreover, as there still a lack in investigating urban planning alternatives for sake of comfort, [6,7], this paper examines how effective manipulating these parameters in establishing urban comfort levels.

Cairo has been chosen as the site for this study because of its rapid growth, hot climate and range of urban planning developments. Cairo is located at 30° 7'N and 31° 23'E. Its population around 16 million people and its rate of expansion over the last 30 years has overwhelmed the master plans developed for the city in 1970, 1982 and 1992.

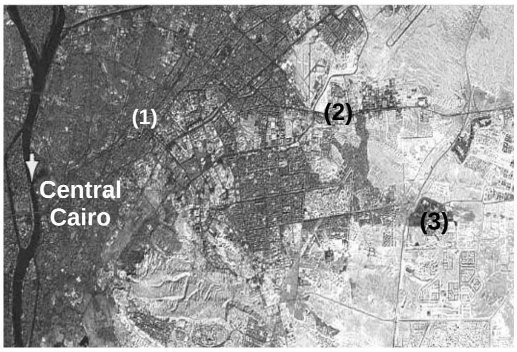

Fig. 1. Location of sites used in study

Different types of urban patterns have been developed as the city sprawled eastwards into the desert and three different urban patterns are analysed in this study – a high density city centre layout, a lower density suburban plan and a dot or single dwellings arrangement. Locations of these sites, shown as 1, 2 and 3 in Fig. 1. Cairo's climate is classified by ASHRAE [8] as mixed dry, semiarid. Based on 30 years of WMO Station no.623660 records at Cairo international airport the extreme hot week period typically lies between 26th June and 2nd July, with a maximum average outdoor air temperature of T_a = 44.0°C and a maximum average summer relative humidity of between 42% and 49% at midday. The maximum average June / July wind speed is 3.5 m/s between from a predominantly NW through to NE direction. The maximum average monthly global radiation levels are 7316 and 6893 Wh/m^2 for June and July respectively.

2. Sites description

2.1 Urban patterns

The 1st urban pattern (shown as 1 in Fig. 1) is high density, compact, multi family, low income apartment housing with a ground floor and four other floors in the central urban area north east to metropolitan Cairo that forms part of the Hadaek Al-Koba district. Fig. 2 shows the urban layout.

Fig. 2. Urban layout at Location 1

The 2nd urban pattern (shown as 2 in Fig. 1) is a mixed clustered-dot, multi family, high income apartments with a ground and three other floors, located in Sheraton Heliopolis urban area of metropolitan Cairo as part of the Misr Al-Gadida district (see Fig. 4).

Fig. 3. Urban layout at Location 2

The 3rd urban pattern (shown as 3 in Fig. 1) is a dot single and multi family, high income villas and apartments with a ground floor and 3 other floors located in the suburban are of metropolitan Cairo outside the first ring road of greater Cairo as part of new Cairo town (see Fig. 4). Table 1 gives some data on the three sites, as they are not equal in area.

3. Methodology

Thermal comfort assessments for the three urban layouts were performed using ENVI-met. It is a three-dimensional microclimate model that can simulate the surface-plant-air interactions within urban environments with a typical resolution of 0.5 to 10 m in space and 10 sec in time. ENVI-met is a prognostic model based on the fundamental laws of fluid dynamics

Table 1: Details of the three sites (A_u is the total urban area of the site, A_g is the ground floor area of all the buildings on the site, C_p is the site construction percentage, C_d is the site construction density ratio and P_d is the site population density ratio for site urban area.

Site	A_u (m^2)	A_g (m^2)	C_p (A_g/A_u)	C_d (A_g/A_u)*no. Of floors	P_d (p/m^2)
1	5621	3839	0.683	3.415	0.758
2	41199	22082	0.536	2.144	0.046
3	62612	21075	0.337	1.008	0.030

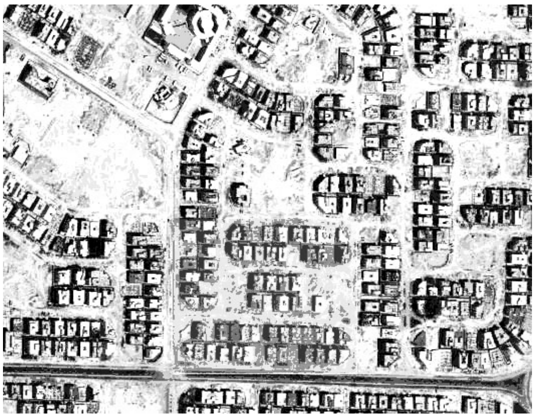

Fig. 4. Urban layout at Location 3

and thermodynamics. The model includes the simulation of flow around and between buildings and the exchange processes of heat and vapour at the ground surface and at walls. ENVI-met is a Freeware program and is under constant development [9]. Outdoor thermal comfort is presented in this paper by the modified Predicted Mean Vote (PMV) at 1.2m a.g.l. PMV predicts the average thermal response (on a scale ranging from 'very hot' to 'very cold') of a group of people exposed to a set of environmental conditions such as air temperature, humidity and wind speed. PMV is calculated in ENVI-met by solving the modified Fanger equation developed by Jendritzky and Nubler, [10], for outdoor conditions, shown in the following eqn.:

$$M + W + Q^* + Q_H + Q_L + Q_{SW} + Q_{Re} + S = 0$$

Where:

M is metabolic rate.

W is mechanical power

Q^* is the radiation budget (a function of mean radiant temperature T_{mrt} and air velocity v)

Q_H is turbulent flux of sensible heat (a function of air temperature T_a and v).

Q_L is turbulent flux of latent heat (diffused water vapour).

Q_{SW} is turbulent flux of latent heat (sweat evaporation).
Q_{Re} is respiratory heat flux (sensible and latent).
S is heat stored.

The mean radiant temperature is calculated in ENVI-met good approximation as mentioned in [11] and that cope with the work of Thorsson et al [12] and the heat balance equation for a surface in an urban canyon which is solved using the work of Kurn et al [13]. The final parameters are the sky view factor (SVF), representing the urban compactness, and the radiant temperature, representing the net radiation received by a human body with an absorption coefficient around 0.7 and an emissivity value of approximately 0.97. The receptor positions chosen for the ENVI-met analysis for each of the three sites are shown in Figs. 5, 6 and 7.

Building materials defined in ENVI-met were constant in all three cases in order to allow only urban form based comparison whilst in good approximation with [14] and [15], for their average properties. As they are built up light grey cement tiled concrete roofs and light grey mortar finished brick walls in the three cases, U and albedo values used in simulations are as following;

U value Walls [W/m^2K]	= 1.70
U value Roofs [W/m^2K]	= 2.20
Albedo of Walls	= 0.30
Albedo of Roofs	= 0.15

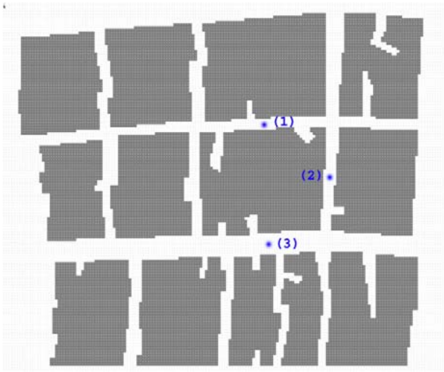

Fig. 5. Receptor positions for Location 1

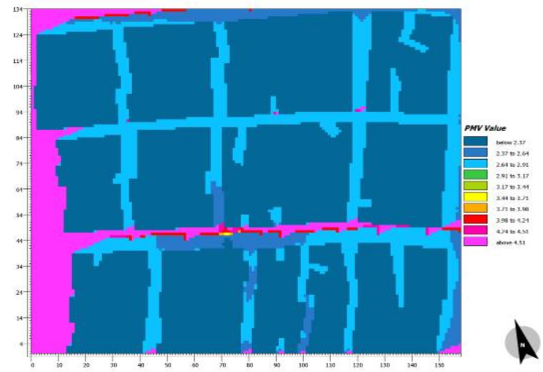

Fig. 8.Outdoor PMV mapping for Location 1, 12.00

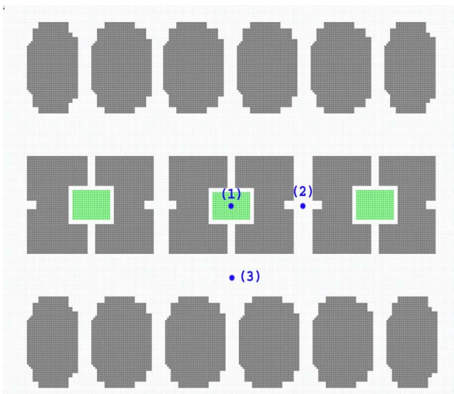

Fig. 6. Receptor positions for Location 2

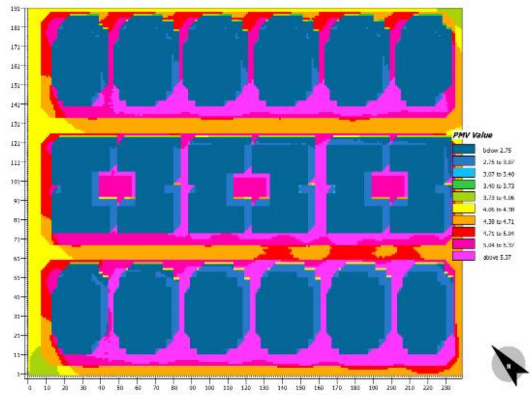

Fig. 9.Outdoor PMV mapping for Location 2, 12.00

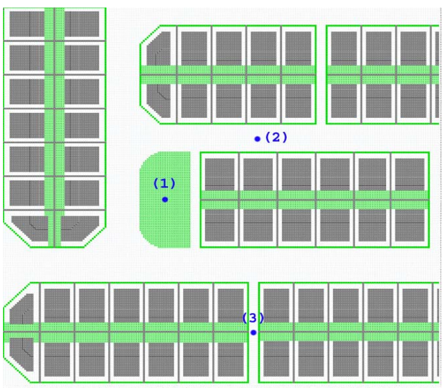

Fig. 7. Receptor positions for Location 3

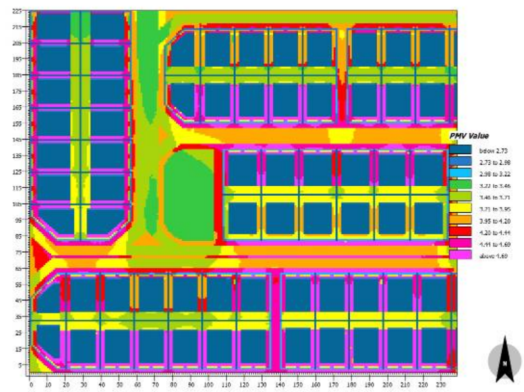

Fig. 10. Outdoor PMV mapping for Location 3, 12.00

4. Results analysis

Simulations were held for three one hour periods at hours - 9.00, 12.00, and 15.00 LST for the hottest period of the year in Cairo (late June/early July). Only the building fabric and green surfaces were modelled for these simulations (no urban trees were modelled) so that only the effect of different pattern forms on the urban canyons' temporal heating regime and comfort levels would be investigated. Figs. 8, 9 and 10 show the site mapping for outdoor PMV for Locations 1, 2 and 3 respectively at 12.00 LST, where the darkest shades represent the lowest PMV values (below 2.34) and the lightest the highest values (above 4.07).

In order to establish that the ENVI-met PMV values were reasonable a validation exercise was undertaken using the Ecotect psychrometric tool [16]. The thermal comfort and weather output data from ENVI-met was 0.5-0.6 Clo, a walking speed of 1.1m/s, 80% RH, wind speed 1.91 m/s and a T_{mrt} of 339.85K. The ENVI-met PMV comfort prediction for the receptor 3 in Location 2 at 11.00 LST was 6.73, which is beyond the PMV scale. The Ecotect tool produced a similarly very hot rating comfort level of 6.60 PMV value, which is in good agreement with the ENVI-met result. This is a remarkable result, but at this point of measurement is black asphalt with no shade on Cairo's hottest day which has been chosen to be simulated as most summer time is implied to be out of comfort in reference to meteorology calculated by [6], it was a research interest to have an idea about its maximum comfort assessment as the cooling degree hours CDH is 1658 at 27° C in June, supposing that further urban climate studies can achieve more effective cooling for the less stress days if the critical day was the design day.

The CFD modelling capacity in ENVI-met allows street level wind speeds to be modelled, and the results for 12.00 LST are shown for the three Locations in Figs. 11, 12 and 13. The sheltering effect of the high density planning in Location 1 is evident, as is the increased air flow in the open spaces at Location 3.

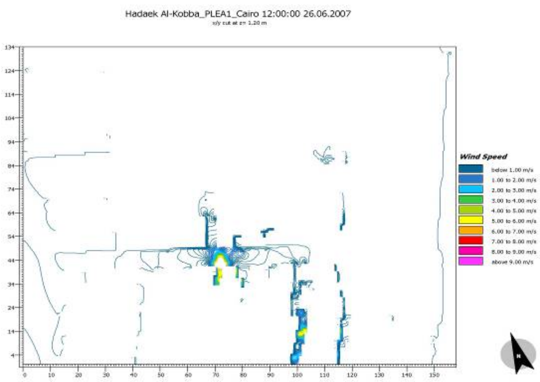

Fig. 11. Wind speed contours, Location 1, 12.00

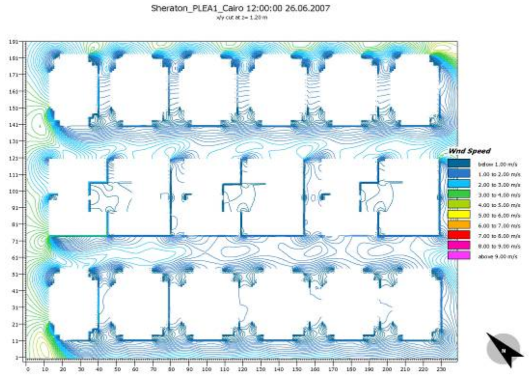

Fig. 12. Wind speed contours, Location 2, 12.00

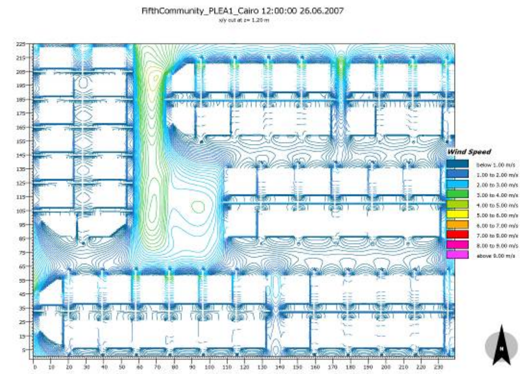

Fig. 13. Wind speed contours, Location 3, 12.00

At Location 1 the PMV was found to have changed for the three receptors from 3.96, 2.66 and 3.96 respectively at 9.00 LST to 2.77, 2.77 and 2.37 at 12.00 LST and 4.22, 2.49 and 4.22 at 15.00 LST. The variations arise from different exposures to direct solar radiation (SVF=0.15, 0.15 and 0.23 respectively) as the wind has almost no access to the site to decrease T_{mrt}. At Location 2 the PMV had changed for the three receptors from 6.31, 6.75, 6.01 at 9.00 LST to 5.20, 5.37, 4.54 at 12.00 and 2.38, 2.38, 4.51 at 15.00 LST. Those high values of PMV at the start of the day then decreasing are due to the open fabric of the three receptor positions of Location 2 (SVF of 0.546, 0.493 and 0.712 respectively) and the sheltering in some of the spaces from air flow. At Location 3 the PMV changed for the three snapshots from 4.19, 5.29 and 5.41 at 9.00 LST to 3.34, 4.08 and 4.69 at 12.00 and 4.20, 5.23, 5.40 at 15.00. Those high values of PMV at 9.00 and 12.00 are due to the canyons orientation that allowed maximum heat gain caused by the sun's position (SVF of 0.85, 0.78 and 0.65 respectively). At receptor position 3, despite its sheltering feature, the confinement (SVF= 0.65) did not allow adequate air movement to release heat stored, convicted and radiated from the lower street levels, hence causing the increased afternoon perception of thermal discomfort.

Relationships between T_{mrt} and SVF were also examined; results are shown in Figs. 14, 15 and 16.

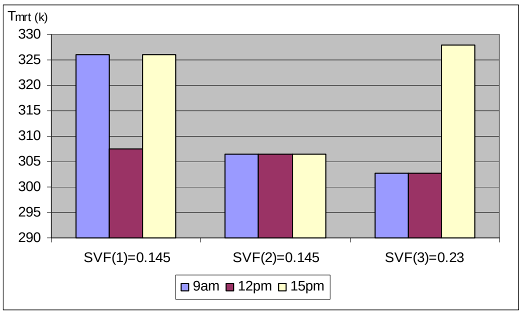

Fig. 14. Relationship between T_{mrt} and SVF and at the three receptors shown in Fig. 5 for Location 1

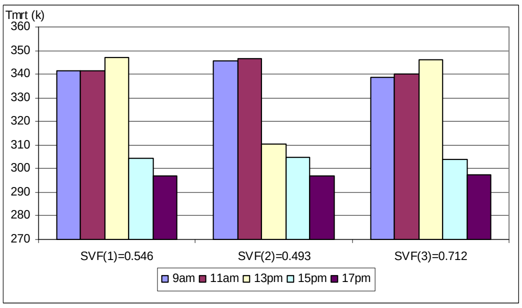

Fig. 15. Relationship between T_{mrt} and SVF and at the three receptors shown in Fig. 6 for Location 2

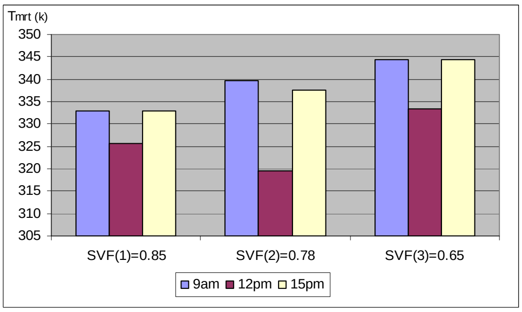

Fig. 16. Relationship between T_{mrt} and SVF and at the three receptors shown in Fig. 7 for Location 3

T_{mrt} has been measured as a biometeorological representation of the all net wave solar radiation of all 6directions from both hemi spheres that access urban spaces and cause radiant exchanges around human body. Consequently, it is a representation of urban fabric compactness.
For example, T_{mrt} at all SVF snapshots at peak time of SVF(2)0.145/1st case is less than 310 K, same is almost for SVF0.493/2nd case whilst about 320 K for SVF(2)0.78/3rd case. SVF(2) values of all cases give an explanation for different T_{mrt}, but the 310 K of SVF(2)0.145/1st case is a bit higher if compared to that of SVF0.493/2nd case of which SVF0.493 is bigger than SVF0.145, the reason is this measurement point canyon's orientation that allows more solar access by this time. Higher values of Tmrt at early evenings can be owed to the short wave radiation of the heat stored by day, which can be noticed at 15.00 LST of SVF(3)/1st case and all SVF snapshots of 3rd case as it is an open fabric.

Note that the T_{mrt} scales are not the same in the three figures and that, in general, higher SVF values are associated with higher T_{mrt} values.

5. Discussion

The concept of urban compactness owes much to the Arabic Saharan urban architecture. This urban planning can be analysed in terms of, firstly, narrow spaces with high aspect ratios and small urban spaces between buildings, height to width for canyons and width to length to height for courtyards. Clustered courtyard form with urban spaces and network that could be confined by trees to replace more compactness help can guide wind and at the same time protect pedestrians within a series of local urban spaces using fine architectural details such as arched alleys, pergolas and colonnaded aisles. Another aspect is the delivery of people from one sheltered space to another via a series of spaces that attempt to ensure microclimate control; the urban consequence are for spaces that can help in controlling the SVF and hence reduce the direct heat gain, radiant fluxes within urban canyons and the whole pattern of the canyon's thermal regime. This was apparent from the close PMV and T_{mrt} values of Location 1 at most places except at 12.00 LST when a high sun and southerly azimuth allowed solar access to the lower main canyon.
In terms of outdoor PMV the high density Location 1 (featured in compactness as traditional Arab urban planning) performed best for the first half of the day but could then not easily dissipate its stored heat in the afternoon due to very low wind speeds. The urban layout for Location 2 in this study can be considered a hybrid urban form between the Arabic vernacular compact urban architecture and the western suburban dot or linear pattern urban form as it has the most recognized Arabic fabric form, the cluster which is a bigger scale of courtyards in medieval Arabic cities. This arrangement performed worst for the first half of the day because of air movement limitations due to the bad closure ratio (H/W/L), and only showed benefits from mid afternoon (where it outperformed the high density layout) when some shading and porosity to air flow combined to cool the urban canyons down. The western style layout of Location 3, perhaps surprisingly, performed generally better than the hybrid arrangement due to an isolated wind flow profile, [6], but only until mid afternoon when the sun could readily irradiate and warm the west and south facing canyons walls. It is apparent from the PMV analysis that the complex interactions between form, density and orientation is leading to a medium density population fabric to reveal in adjusted compactness degree.

6. Conclusion

The transient conditions of urban climate aren't completely controllable rather to be enhanced; all of the three cases are out of comfort levels (if acclimatization hasn't been counted). The compactness of each urban pattern case in terms of SVF, aspect ratios, and the pattern design details have played role in differentiating PMV and T_{mrt} values in each case. The high and low compact urban designs examined in this study cannot necessarily achieve these objectives. The highly populated urban housing in 1st case revealing in compact form is better in thermal performance by day but not same by night whilst not preferred from urban health point of view as it hasn't sufficient wind access besides the high population density itself. A medium density population fabric that can produce medium aspect ratios and medium SVF values can experience enough wind speed and solar access for both passive cooling and health aspects, but its canyon aspect ratios didn't support enough shelter at higher solar vertical positions which can be enhanced by vegetation and urban trees if considered and is not available for the compact form also. Moreover, its clustered form proportions didn't allow wind access through the cluster's courtyards which if studied in addition to orientation in relation to northern prevailing wind may allow enough ventilative alleviation. In opposite to 1st case, the 3rd case have enough wind flow access but more incident surfaces for direct radiation with a lower population density among the three cases, which is more land consumption, sprawl and needs much more green cover and urban trees if compared with 1st and 2nd cases. The urban hybrid cluster can be an improvement for the traditional Arabic urban form by utilizing medium density court yarded fabric such as in 2nd case to achieve suitable urban site over all compactness degree by clusters closure ratio (H/W/L). After all, this study shows that an urban passive form design can be optimized using spatial networks with orientation, fabric unit with urban spaces to conclude an adequate compactness degree upon specific housing and population providing shelter while allowing wind flow access for urban spaces cooling which can be called a hybrid urban form.

7. Acknowledgment:

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