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Visual Thermal Landscaping (VTL) Model: A Qualitative Thermal Comfort Approach based on the Context to Balance Energy and Comfort

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Abstract

The Visual Thermal Landscaping (VTL) model provides a practical solution to balance energy and comfort tailored for the context and the immediate needs of individual occupants in that context through a thermal visualisation analysis. The aim is to provide a solution to the limitations of current tools employed in practice which do not account for the richness of thermal experience, which is never neutral. This disconnect between analysis tools and experience results in buildings using more energy than they should and leaves occupants dissatisfied with their environment. The capabilities of the approach were demonstrated through a field survey in an open plan office building, which was naturally ventilated and very energy efficient, as is reflected in its BREEAM excellence award. The model demonstrated the complexity of thermal comfort through contextual analysis. It illustrated individual differences in perceiving the thermal environment and the dynamic aspect of thermal comfort (i.e. occupants change their mind). Hence, a particular room temperature cannot satisfy everyone all the time. This holistic qualitative approach enables to provide comfort for every individual as well as a strategy to lower the overall energy consumption of the building. The immediate results of the model can be used by facilities management systems and the future development of the model can be used to predict areas and periods of thermal discomfort, provide additional support for the use of energy efficiency measures, and promote the use of thermal diversity in buildings.

Keywords: Visual Thermal Landscaping (VTL); Personal Comfort Systems; Dynamic Comfort; Thermal Comfort; Energy

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1. Introduction

One of the main purposes of a building is to provide a comfortable and satisfactory environment for occupants [1]. Many researchers found that user satisfaction is highly related to the quality of the thermal environment [2]. Balancing energy and comfort is a challenge, and most workplaces perform at one end and at the expense of the other end [3]. In the developed countries, up to 50% of the energy consumption in the building is due to thermal performance [4]. Buildings with poor thermal management suffer from low user satisfaction and high energy consumption [5]. Increasing individual control over the environment has the potential in reducing the energy use of the building [6]. Bordass et al [7] state that 'modern control and energy management systems offer the potential to improve individual comfort and reduce energy consumption at the same time'. Nicol and Stevenson [8] recommend the adoption of adaptive opportunity as part of the design of the buildings as an effective strategy to tackle climate change as well as energy and economic challenges. It is a challenge to satisfy all in a shared environment [9], due to individual differences in perceiving the thermal environment and the dynamic aspect of thermal comfort (meaning occupants keep changing their mind) [9]. However, the ASHRAE claims to provide comfort for over 80% of the occupants through the standard comfort zone [10]. Despite Fanger's Predicted Mean Vote (PMV) model being based on the neutral temperature assuming thermal comfort [11], occupant discomfort is reported [12].

The design of the workplace is disconnected from the user, as it has 'little to do with what the man at his desk really needs' [13]. Currently, in order to simplify the complexity of thermal comfort in the workplace, most managements prefer to remove occupant control over the thermal environment and to replace it with centrally controlled thermal systems [7, 14]. However, researchers report occupants' dissatisfaction regarding the lack of user control over the thermal environment [15] and the history of the workplace is overwhelmed with users' request to control the thermal environment (e.g. opening a window) [16]. Some researchers go as far as predicting user thermal control as a required asset in the office buildings in the future [17]. Companies, which prioritise attracting talented workforce, consider providing a pleasant thermal environment and hence the application of personal thermal control as an effective strategy [18]. In a study, Kroner [19] reports that in an office building were Personal Comfort Systems (PCS) were provided, employees rejected other job offers because of the PCS. This study investigates the application of a new qualitative visual technique method to analyse personal thermal comfort according to the context and other occupants in depth. The Visual Thermal Landscaping (VTL) model was applied on the collected data from twelve occupants and their context of a workplace in Scotland in Summer with the aim to provide practical solutions for improving thermal comfort of the occupants and energy performance of the building.

2. Previous Related Work

Traditionally, quantitative methodologies have been used in the field of thermal comfort. Quantitative methodologies are valuable when generalising; however, the "voice" of the participant is not reflected and their use of context is limited [20]. In contrast, a qualitative approach highlights 'behaviour in context' through a systematic approach [21]. This kind of method is suited to explore how participants make sense of their environment in the context of daily life, as their use is in analysis and interpretation of phenomena in their natural settings [22]. Hitching [23] suggests the application of qualitative methodologies in thermal comfort to lead to new discoveries. Currently, the PMV and adaptive comfort models are the most common methods in predicting the thermal comfort, which are used by thermal comfort standards, including ISO [24] and ASHRAE [25]. Climate chambers and field studies of thermal comfort are the main methodologies [26], in which similar data is collected regarding occupants and the environment. Their main difference is the consideration of context in field studies and the lack of a daily context in the experiments, as it takes place in a lab [22]. The findings of experimental chambers may not apply to the real world contexts [27], while the results of the field survey are more applicable [27]. However, their difference is mainly in the location of the study (i.e. workplace compared to a lab) rather than their approach and the use of contextual information. During the analysis, relatively similar quantitative methods are applied in both methods. Field studies are limited in the extent of using the contextual data and their analysis lack depth, meaning, connections, and the voice of the occupant; these qualities could lead to new discoveries (e.g. patterns of behavior). The accuracy of both PMV and adaptive models, when applied to the real context of the workplace and their application in small group of individuals, have been criticised [28, 29]. Kim et al [39] state that 'the model properties (e.g., function, coefficients) are fixed by the original data set (i.e., laboratory data for the PMV model, and field data for the adaptive models), and cannot be updated to reflect the actual comfort conditions of individuals in a particular setting'. Recently, based on the criticism for the PMV and adaptive models, new methods are being introduced, such as machine learning methods [28, 30, 31]. The Personal Comfort Model was introduced to predict the thermal preferences of individuals through machine learning with the ability to adapt according to the new data input [30]. To this end, no work has applied a holistic approach to analyse personal information in depth and directly to the context and in connection to other occupants.

3. Research Methods

This research follows the grounded theory , where several hypothesis are considered and during the journey of the study the theory emerges [22]. This is in line with the application of a qualitative method and particularly the use of visual analysis. Graphical visual analysis is recently used by many researchers, such as economists, biologists and mathematicians [32]. In thermal comfort field, visualising the data in the context provides a platform to derive meanings, connections between the data and patterns according to the meaning and context. It allows a fresh view of the field using a holistic approach (i.e. analysing all aspects and their connections in one go), which can be used to question the existing theories and their assumptions (e.g. thermoneutrality) and to introduce new hypotheses. This study investigated the application of an innovative qualitative Visual Thermal Landscaping (VTL) model to holistically analyse the collected data. Environmental, personal and contextual information are monitored, such as environmental measurements (e.g. dry bulb temperature, relative humidity and mean radiant temperature), occupants' views (e.g. overall comfort, satisfaction, thermal sensation and preference ASHRAE seven-point scale [33]) and contextual information (e.g. seating arrangements, teamwork and work performance criteria). The data collection was repeated three times a day: morning (09.00-12.00), noon (12.00-14.00) and afternoon (14.00-16.00). The study was applied in an open plan office in the UK in July. The building was naturally ventilated and very energy efficient (BREEAM excellence). Twelve occupants participated in the study, including seven males and five females. The collected data was visualized and analysed using the proposed VTL model, as presented in Fig 1.

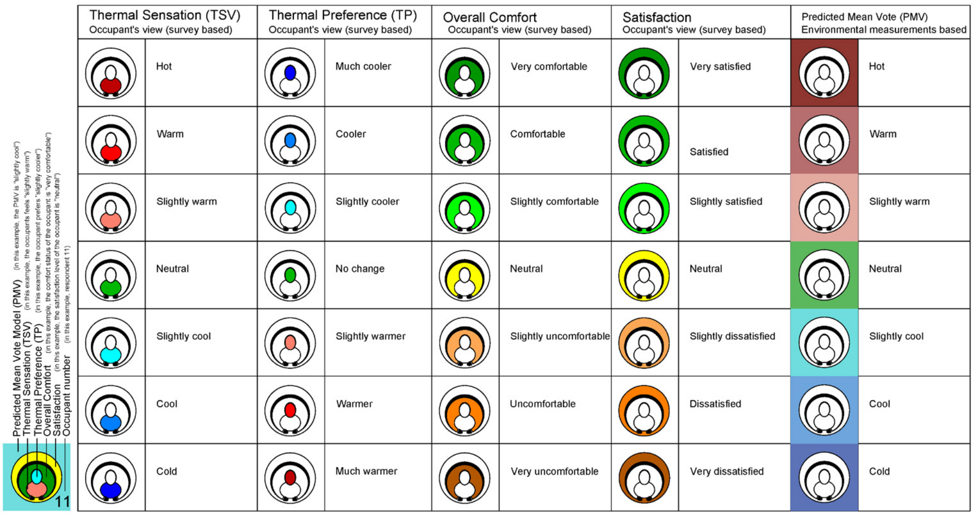

Fig. 1. The legend for the colour coding used in the Visual Thermal Landscaping (VTL) model

The present practical use of the VTL model is demonstrated in Fig 2. Through constant monitoring the thermal environment and allowing occupants to express their views through available surveys, the information can be available to the facilities manager/management via the VTL model. Since the green colour shows satisfactory conditions (e.g. no change preference), any migration from this colour can be easily spotted and in case majority of occupants seated close by have similar views and dissatisfaction, relevant adjustment of the thermal environment (e.g. heating or cooling) can be applied immediately. In future work, the VTL model can be connected to machine learning systems to adapt the thermal environment according to the recognised personal occupant's preferences.

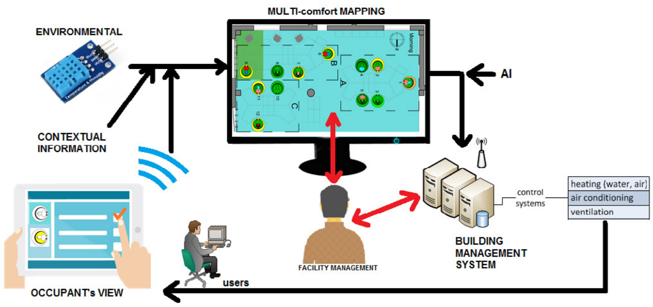

Fig. 2. How the VTL model fits in the existing analysis workflows in professional practice

4. Results and Analysis

Fig 3 illustrates the mapping of all information regarding the respondents in the context of their office three times a day. Based on the VTL analysis, the following occupancy categories were recognised:

- *High tolerance:*

They have consistently a "no change" preference regardless of the changes in the thermal environment or their thermal sensation; less sensitive to the changes of the thermal environment, such as occupants 3, 5, 8, and 10.

- *Consistent directional preference:*

They have mainly a particular preference towards either cool or warm; they change their mind, but still in the same direction (e.g. slightly cooler in the morning and cooler in the afternoon), such as occupants 1, 6, 7, 11, and 12.

- *Fluctuating preference:*

They have different and opposite thermal preferences at different times and may not be directly related to the temperature changes (e.g. slightly cooler when PMV is slightly cool, and warmer when PMV is neutral), such as occupants 2, 4 and 9.

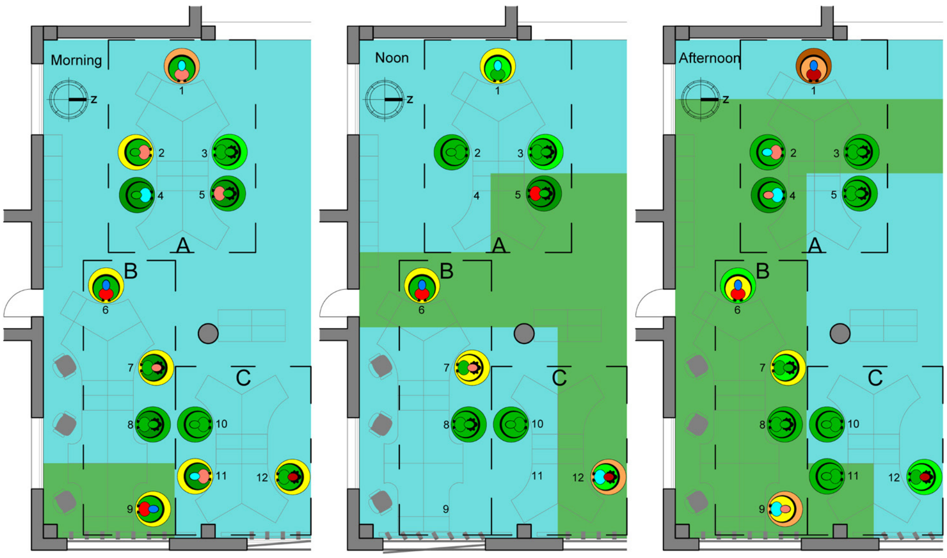

Fig. 3. The Visual Thermal Landscaping (VTL) model demonstrates views of the occupants in the office in the morning, noon and afternoon

This holistic approach allows analysis of each occupant according to the context. It is important to acknowledge the working teams (e.g. marketing and finances), in which team members are expected to seat close by to benefit from the ease of communication and knowledge transfer. In this study, groups A, B and C represent these teams. Analysis and solutions were given according to the teams as well as the above mentioned categories. For example, in team C, occupant 10 constantly feels neutral, prefers no change and he is comfortable throughout the day, while the PMV predicts slightly cool all day in his workspace. Occupant 11 prefers slightly cooler when the PMV is already slightly cool, but prefers no change when the temperature has increased and PMV is neutral, suggesting different preferences regardless of the thermal conditions. Occupant 12 experiences different thermal conditions from neutral to slightly cool, her thermal sensation is not in line with the changes of the thermal environment (feels neutral when PMV is slightly cool, and feels slightly cool when the PMV is neutral). However, her thermal preference is constantly much warmer.

It is recommended to move occupant 12 away from the window and the potential draught to the forth desk and to provide her with heating PCS (e.g. warmed chair). Occupant 11 may benefit to sit closer to an openable window and cooling PCS (e.g. desk fan or cooled chair). These suggestions are based on one-day holistic analysis; in order to confirm their accuracy, further longitudinal analysis using the VTL model is recommended. This analysis shows the complexity of comfort, the extent of individual differences seated close by and how they change their preferences during the day (i.e. dynamic comfort). They show that no simple solution such as reducing or increasing the room temperature can result in comfort for all, as these occupants prefer different changes. This building is naturally ventilated and currently no energy is being used to cool or warm the building. The PMV model predicts a slightly cool conditions in the morning, suggesting an increase in the temperature should result in higher comfort level of the occupants. In order to achieve this, additional heating (e.g. radiator) is required to operate, which results in using more energy. However, only two occupants prefer slightly warmer or warmer and the rest either prefer no change or slightly cooler to cooler. This suggests that by increasing the temperature and using energy, 10 out of 12 occupants will become less comfortable.

5. Discussion, Conclusion and Future Works

The results indicated that by simply relying on the traditional models in the field and their predictions, results in overlooking the context and individual preferences within that context. Therefore, the consequence is more likely to use more energy while making the occupants more uncomfortable. It reveals the complexity of thermal comfort regarding individual differences in perceiving the thermal environment, changes of occupants' preferences, and the fact that a particular thermal environment cannot satisfy everyone all the time. The VTL model includes the contextual information, such as the fact that occupants may not have the liberty to seat, where they find the thermal conditions as comfortable, due to teamwork, knowledge transfer and other constraints. Based on the analysis of the VTL model and the changes in the thermal preferences of the respondents within the thermal context, three categories of occupants were recognised: high tolerance, consistent directional preference and fluctuating preference. The recommendation is to provide a personal comfort system with uni-functional ability (i.e. either warming or cooling) for the consistent directional preference individuals and to provide a personal comfort system with both warming and cooling facilities for the fluctuating preference occupants. Also, some recommendations were made to increase individual comfort level while reducing the energy use, as follows:

- In order to reduce the energy use of the building, to keep the room temperature towards the lower or higher boundaries of the standard comfort zone according to the season (e.g. lower temperatures in winter and higher temperatures in summer). The adoption of sustainable architectural strategies to achieve this is highly recommended to further reduce the energy consumption of the building.
- To change the room temperature only when the majority of the occupants prefer either cooler or warmer temperatures and their comfort and satisfaction levels drop (e.g. the colour of the TP for most occupants turns blue demonstrating that they prefer slightly cooler and their comfort and satisfaction orange illustrating their discomfort and dissatisfaction).
- Consistent directional preference towards warmer: these occupants benefit from seats away from the window and potential draught and radiant effect. The availability of PCS with warming functions increases

their comfort level.

- Consistent directional preference towards cooler: these occupants benefit from a window seat and the potential breeze. The availability of PCS with cooling functions increases their comfort level.
- To keep the occupants with opposite consistent directional preferences as far apart as the teamwork and arrangements make possible
- To have a close seating arrangement for the high tolerance individuals and in case possible between the individuals with opposite consistent directional preferences.
- The fluctuating preference individuals benefit from PCS with both warming and cooling functions, so that they change the thermal settings according to their requirements.

The Visual Thermal Landscaping (VTL) model presented in this work provides in depth understanding of the user as an individual as well as part of the context and environment. It allows interpretation of the data according to the context, meaning, connections between the data, and it reflects the voice of the occupant. This method enables the emergence of further theories and discoveries in the field of thermal comfort. This holistic qualitative approach enables to provide comfort for every individual as well as to develop a strategy to lower the overall energy consumption of the building. The personalised approach is recommended to be considered as part of the architectural and engineering design of the building. The immediate results of the model can be used by facilities management systems and the future development of the model can be used as part of machine learning systems to predict and to provide thermal comfort for every individual while reducing the overall energy consumption of the building. Further research in this area as well as relevant energy strategies are recommended.

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