Thermal comfort perception and indoor climate: Results from the OPSCHALER project

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Abstract. The average energy consumption for heating of dwellings in the Netherlands has been decreasing over the last decades as a result of increasing thermal performance of new and renovated dwellings. However, this decrease is found to be lower than energy performance models predicted. One of the possible reasons is the behaviour of the residents, which is partially determined by the thermal comfort preferences of these residents. In this paper, the relationship between thermal comfort perception, indoor climate and energy consumption is investigated using high-resolution measurement data in 93 dwellings in the Netherlands. In the OPSCHALER project, data about thermal comfort perception, indoor climate and operational energy consumption were collected in 93 dwellings in the Netherlands during periods ranging from two to twelve months over a period of two years. Comfort perception was registered using the Comfort App, an application where users record their comfort data. Indoor climate data were collected per five minutes using sensors for temperature, relative humidity and CO2 concentration in the living room, kitchen and bedrooms of the dwellings. The Comfort App asked the residents for the room they are in, their comfort perception, their activities during the last half hour and the amount of clothing they wear. Significant relationships were found between thermal sensation and thermal preference, clothing level, metabolic activity level, activities related to thermal comfort taken in the last half hour, and indoor air temperature. These data can be used to compare the comfort level registered by the residents with the comfort level predicted by the PMV model, and link this to the indoor climate and the energy consumption for heating. This information can help to understand the relations between user preferences, indoor climate and energy consumption for heating.

Keywords. Thermal comfort, indoor climate, dwellings, comfort theory
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1. Introduction

According to the European Commission, buildings are responsible for approximately 40% of the EU energy consumption and 36% of the CO_2 emissions. The residential building sector takes 63% of this share [1]. To meet the goals for reduction of CO_2 emissions as stated in the Paris Agreements [2], a significant effort is needed to reduce energy consumption in the residential sector, both in new and in existing houses. However, energy renovations in existing houses were found to result often in lower energy savings than estimated from energy models. One of the reasons are differences in energy consumption of dwellings with similar characteristics. It has been shown that the energy consumption of similar dwellings may differ up to 3 times [3,4]. At the same time, several studies have concluded that there is a difference between the actual and the predicted energy consumption, the so-called "energy performance gap", with differences reaching up to a factor of 2 [5-7]. Current simulation software is simplified and does not take residents' energy related behaviour largely into account [8]. This behaviour is largely related to the comfort perception of the residents.

The most widely used thermal comfort models for assessing thermal sensations are Fanger's Predictive Mean Vote or the PMV model [9] and the adaptive thermal comfort model [10]. These theories have been tested in the past on small scale, but large testing using large scale monitoring campaigns in many dwellings over an extended period has not often been carried out. These monitoring campaigns can yield data that can be used to test the comfort perception models, which can then be used to improve energy consumption models for dwellings.

In this paper, the relationship between thermal comfort perception, resident characteristics and indoor climate is investigated using high-resolution measurement data in 93 dwellings in the Netherlands.

2. Methodology

2.1 Data collection

In the OPSCHALER project, data about thermal comfort perception, indoor climate and operational energy consumption were collected in 100 dwellings in the Netherlands during periods ranging from two to twelve months over a period of two years (2017-2019). The dwellings are privately owned houses, located in several areas in mid, west and southwest Netherlands. The choice of the dwellings was based on the willingness of the residents to participate with the monitoring campaign and on the presence of a smart meter for gas and electricity consumption.

The thermal comfort perception was monitored using a tailor-made app (ComfortApp) that the residents could use on their phone or tablet. In the ComfortApp, residents were able to fill in various subjective data such as:

- Perceived comfort level (thermal sensation) on a 7-point scale, from -3 (very cold) via 0 (neutral) to +3 (hot), as well as preferred comfort level (thermal preference), from -1 (cooler) to +1 (warmer)
- The room they are occupying when filling in the log
- Clothing level (6 levels)
- Metabolic activity level: lying /sleeping, relaxed sitting, doing light deskwork, walking, jogging, running.
- Actions taken during the past half hour related to comfort and energy consumption

The residents of the houses were asked to fill in the app a few times per day (preferably in the morning, midday and evening), but no reminders could be given, so the input in the ComfortApp depended on the initiative of the residents. For each dwelling, two accounts for the ComfortApp were available, but in most cases, only one family member used the ComfortApp. The data from the ComfortApp were directly stored in a central project database.

Indoor climate was monitored using sensors developed by Honeywell that monitor temperature, relative humidity, CO_2 concentration and presence in the room. The sensors were installed in four rooms (of available, else fewer sensors were installed) in each dwelling: living room, kitchen and two bedrooms. The measuring frequency of all sensors was 5 minutes. The value recorded for each 5-minute interval was the average of the readings during that interval. Further information on the sensors can be found in [11].

The operational energy consumption was monitored using the smart meter for gas and electricity consumption that was present in each house, provided by the grid operator and used for billing. The meter readings and actual power were collected from the available data port on the meter (P1 port) using a wireless device called Cloudia. This device, developed By Technolution, send the data to a central server of this company, which directly sends the data to the database of the research project. The meter readings for the electricity consumption are collected once per 10 seconds, and for the gas consumption once per hour.

Additional characteristics of the dwellings (installations, insulation, room size, etc.) were gathered during a visual inspection round by the project workers during installation of the sensors. The list of data collected during this inspection was sufficient to determine the energy label of the dwellings [12].

Finally, the resident characteristics were investigated using a survey that the residents filled in during the installation of the sensors. In this survey, questions on the residents, daily presence in the dwelling, use of the installations and other energy-related questions were asked.

All data were treated as privacy sensitive data, meaning that the data analysis and reporting were done anonymously and that the dwellings in the reporting cannot be traced back to the actual dwelling or resident.

2.2 Data analysis

Before data analysis, the data were cleaned from illogical or (possibly) incorrect datapoints. The thermal comfort perception data were cleaned by removing the first two datapoints on the date of installation, which may be entered as imaginary data during the demonstration of the ComfortApp to the residents. Dwelling which after this step had no thermal comfort data were excluded from this research.

Indoor climate data were cleaned by removing empty values and values that are above a certain threshold (35 °C for temperature, 100% for relative humidity), or far below the background concentration (400 ppm for CO_2 concentration). For the dwelling inspection, contradictory findings were removed.

The thermal comfort data were divided between datapoints taken in winter (October-March) or taken in summer (April-September). This distinction was made because during winter months, a relatively warm environment is often considered less a problem in summer than in winter, and in summer, outdoor temperatures are usually higher, leading to a different thermal sensation. Because of the relatively low number of dwellings in this analysis, all individual datapoints for thermal comfort were regarded; no aggregation on dwelling level were made, because the thermal comfort perception of an individual can change during the day.

Indoor air temperatures in the living room and in the kitchen of the last half hour were averaged for each datapoint and used for the comparison with the thermal comfort and thermal sensation.

The thermal sensation was plotted against the month of the year, the thermal preference at the moment that the datapoint was registered, and the indoor air temperature in the living room. The thermal preference was also plotted against the indoor air temperature in the living room. The significance of the relations between the thermal sensation and the thermal preference, thermal sensation and clothing level, thermal sensation and metabolic activity level, and thermal sensation and activities related to thermal comfort that were done in the last half hour before the datapoint was taken, were tested using a Pearson's Chi-square test. The relation between thermal sensation and indoor air temperature, and between thermal preference and indoor air temperature, was tested using a multinominal logistic regression.

3. Results

3.1 Data cleaning and overview

The data collection could not or partially take place in a few dwellings because of several practical reasons such as malfunctioning of equipment or mistakes in inspections. Therefore, for several data types there are date for fewer than the 100 dwellings in the project. An overview of the available data is given in Table 1.

3.2 Thermal comfort

Figure 1 shows the total number of datapoints for the thermal comfort perception per month (winter months in blue, summer months in red). In winter, 3486 datapoints were taken, and in summer, 4268 datapoints were taken for thermal comfort perception.

Tab. 1 – Available data in OPSCHALER dataset.

Type of data	Number of dwellings
Thermal comfort perception	83
Indoor climate	81
Energy consumption	78
Dwelling inspection	83
Resident survey	83

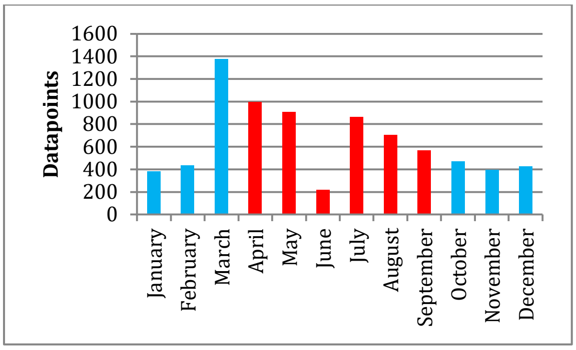

Fig. 1 – Number of datapoints for thermal comfort perception (blue: winter; red: summer).

Figure 2 shows the distribution of thermal sensation in winter, and Figure 3 shows it for summer. The distribution of thermal comfort perception levels in both winter and summer shows roughly a bell curve, which is in line with the thermal comfort perception theories [9, 10].

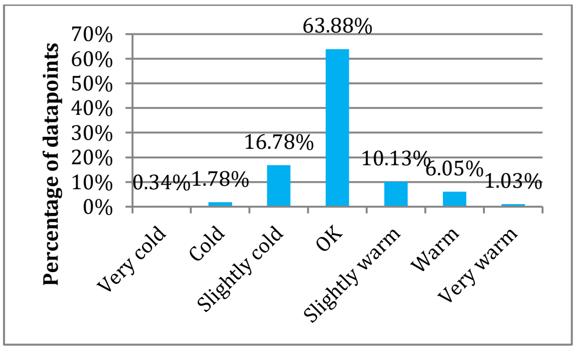

Fig. 2 – Percentage of datapoints for thermal sensation per perception level (winter).

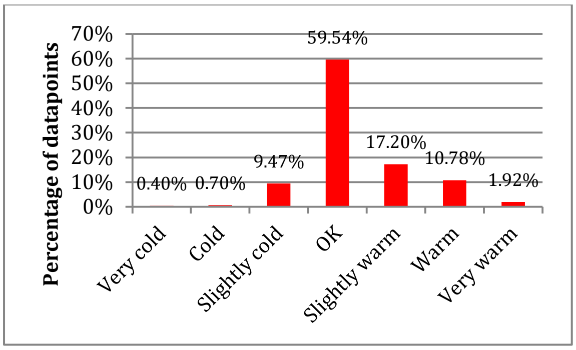

Fig. 3 – Percentage of datapoints for thermal sensation per perception level (summer).

Figure 4 shows the share of comfort preference per datapoint for thermal comfort perception in winter, and Figure 5 shows it for summer.

In winter, the majority of residents that feel warm are OK with this, with a small share having the preference to feel colder. The majority of residents that feel cold, however, have a preference to feel warmer, except for residents that feel very cold. The large share of residents that feel very cold but are OK with it is possibly a bias caused the low number of datapoints (12) in that category.

In summer, a large share (23-57%) of the residents that feel warm have a preference to feel cooler, and the majority of the residents that feel cold have a preference to feel warmer, except of residents that feel very cold (possibly a bias caused by the low numer of datapoints (17) in that category.

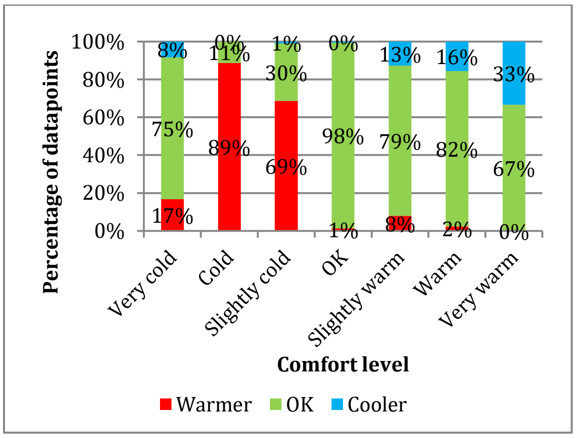

Fig. 4 – Percentage of thermal preference per thermal sensation level (winter).

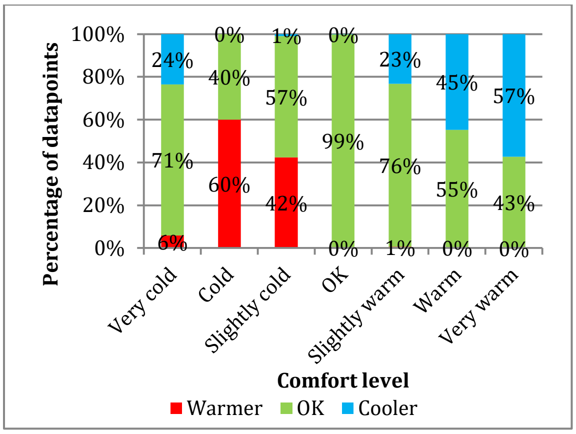

Fig. 5 – Percentage of thermal preference per thermal sensation level (summer).

A Chi-square test was performed on the relation between the thermal sensation level and thermal preference. The null hypothesis was: “The thermal sensation is not related with the thermal preference”. The crosstabulation table is given in the analysis report [11]. The test results of the Chi-square test are given in Table 2. All requirements for the Chi-square tests are satisfied. For a significance level of 0.05, both for winter and summer the p-value is 0.000, which is below 0.05, and the null hypotheses are rejected. This means that there is a significant relationship found between thermal sensation and thermal preference for the dwellings in this research.

Tab. 2 – Chi-square test results for the relation between thermal sensation and thermal preference for winter and summer.

	X^2 value	df	Asymptotic significance (2-sided)
Winter			
Pearson Chi-square	2286.219[a]	8	0.000
N of valid cases	3486		
Summer			
Pearson Chi-square	2741.655[b]	8	0.000
N of valid cases	4268		

[a]: 1 cells (6.7%) have expected count less than 5. The minimum expected count is 2.27.

[b]: 2 cells (13.3%) have expected count less than 5. The minimum expected count is 2.26.

The thermal sensation has also been tested using a Chi-square test against the clothing level of the residents, the metabolic activity levels, and actions taken during the half hour before the reporting of the thermal sensation. Details of these analyses can be found in [11]. The conclusions of these tests are given in Table 3. All requirements for the Chi-square tests are satisfied. For all relationships tested and for a significance level of 0.05, both for winter and summer the p-value is 0.000, which is below 0.05, and the null hypotheses are rejected. This means that there is a significant relationship found between thermal sensation and clothing level, metabolic activity level and actions taken during the half hour before the reporting of the thermal sensation.

Tab. 3 – Chi-square test results for thermal sensation and clothing level, metabolic activity level and actions taken during the half hour before the reporting of the thermal sensation, in winter and summer.

	X^2 value	df	Asymptotic significance (2-sided)	N of valid cases	# cells with expected cound <5	Minumum expected count
Thermal sensation – clothing level (winter)	191.947	12	0.000	3486	0 (0.0%)	5.71
Thermal sensation – clothing level (summer)	420.704	12	0.000	4268	1 (5.0%)	1.96
Thermal sensation – metabolic activity level (winter)	172.189	20	0.000	3486	1 (3.3%)	1.80
Thermal sensation – metabolic activity level (summer)	93.747	20	0.000	4268	2 (6.7%)	1.01
Thermal sensation – actions taken in past half hour (winter)	902.970	44	0.000	6627	8 (13.3%)	0.52
Thermal sensation – actions taken in past half hour (summer)	417.859	44	0.000	8175	7 (11.7%)	0.84

3.2 Relation between thermal comfort and indoor climate

Figure 6 shows the relation between thermal sensation and indoor air temperature (averaged over the half hour before the datapoint was collected) in the living room for all dwellings in the dataset. Figure 7 shows the relation between thermal preference and indoor air temperature (averaged over the half hour before the datapoint was collected) in the living room for all dwellings in the dataset. The width of the line shows the relative number of datapoints for that particular thermal comfort/temperature datapoint. The thermal sensations and thermal preferences were used without considering activities or metabolic rates of the residents. It was found that in most of the dwellings, the temperature is between 15°C and 30 °C. For datapoints with thermal sensation warmer than average, the average indoor temperature seems slightly higher than for datapoints with thermal sensation colder than average. The average indoor temperature is slightly higher for datapoints where the thermal preference is 'cooler', and slightly lower for datapoints where the thermal preference is 'warmer'.

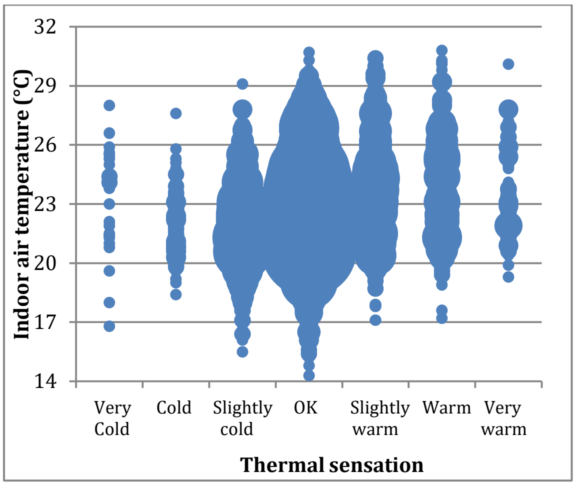

Fig. 6 – Indoor air temperature in living room for all thermal comfort datapoints, given per thermal perception level. The width of a datapoint shows the relative number of datapoints at that coordinate.

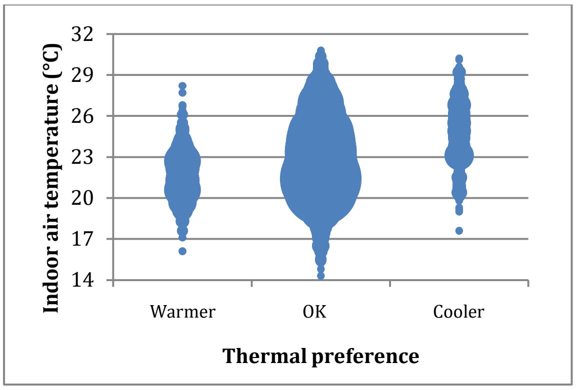

Fig. 7 – Indoor air temperature in living room for all thermal comfort datapoints, given per thermal sensation level. The width of a datapoint shows the relative number of datapoints at that coordinate.

The significance of the relation between thermal sensation and indoor air temperature, and between thermal preference and indoor air temperature, was tested using a multinominal logistic regression. The null hypotheses for these tests are respectively "The thermal sensation is not related with the indoor air temperatures" and "The thermal preference is not related with the indoor air temperatures.". The regression results are given in Table 4 for the thermal sensation and Table 5 for the thermal preference. The column 'Sig.' gives the significance of the relation, and the column 'Exp(B)' gives the factorial increase or decrease of the probability compared with the value for 'OK'. The significance for the regression results are all below the significance level of 0.05, except for the difference between the thermal sensation level 'very cold', which is possibly caused by the low number of datapoints in this category. The null hypotheses for the relations between indoor air temperature and both thermal sensation and thermal preference can therefore be rejected, and there is found a significant relationship between indoor air temperature and both thermal sensation and thermal preference.

Tab. 4 – multinominal logistic regression results for the relation between thermal sensation and indoor air temperature in the living room of all project dwellings.

								95% Confidence interval for Exp(B)	
Preference		B	Std. error	Wald	Df	Sig.	Exp(B)	Lower bound	Upper bound
Very cold	Intercept	-6.245	1.961	10.148	1	0.001			
	Temperature	0.054	0.084	0.410	1	0.522	1.056	0.895	1.245
Cold	Intercept	-0.262	1.107	0.056	1	0.813			
	Temperature	-0.158	0.050	9.898	1	0.002	0.854	0.774	0.942
Slighlty cold	Intercept	2.119	0.392	29.206	1	0.000			
	Temperature	-0.162	0.018	84.461	1	0.000	0.850	0.821	0.880
Slighlty warm	Intercept	-5.122	0.393	169.567	1	0.000			
	Temperature	0.152	0.017	83.449	1	0.000	1.164	1.127	1.203
Warm	Intercept	-5.640	0.477	139.751	1	0.000			
	Temperature	0.154	0.020	58.959	1	0.000	1.167	1.122	1.214
Hot	Intercept	-7.131	1.026	48.268	1	0.000			
	Temperature	0.148	0.043	11.747	1	0.001	1.159	1.065	1.262

Tab. 5 – multinominal logistic regression results for the relation between thermal preference and indoor air temperature in the living room of all project dwellings.

								95% Confidence interval for Exp(B)	
Thermal sensation		B	Std. error	Wald	Df	Sig.	Exp(B)	Lower bound	Upper bound
Warmer	Intercept	3.235	0.445	52.781	1	0.000			
	Temperature	-0.240	0.020	139.220	1	0.000	0.797	0.756	0.819
Cooler	Intercept	-9.548	0.582	268.919	1	0.000			
	Temperature	0.297	0.024	147.721	1	0.000	1.333	1.272	1.396

4. Discussion

This paper shows that several significant relationships were found between different thermal comfort parameters regarding the resident indoor and air temperature were found. However, the conclusions should be drawn with care, because of limitations in the data and in the research set-up.

The first limitation is the relatively low number of dwellings. The project dwellings are common dwellings that can be found in many places in the Netherlands, but are not a good cross-section of the Dutch housing stock in terms of dwelling type, ownership (most dwellings in the project are owner-occupied) or age, and can differ significantly from dwellings in other countries. Therefore, generalisations of the results presented in this paper should be made with care.

There is some uncertainty regarding the separation of the data between winter and summer. The separation was made based on the theory that heating of the dwellings is required from October till March not in April till September, but this is not always the case.

The analysis of the thermal comfort data was done without regarding the room of the dwelling or the time of the day of the reported thermal sensation. Most datapoints were reported by the residents while being in the living room and were quite uniformly distributed throughout the day with most data points in the evening.

The thermal comfort data were registered by the residents themselves using the ComfortApp. This means that the data on presence in which room, the clothing level and activities taken are self-reported and could deviate from the actual situation, leading to small errors in the comfort data. It is assumed, however, that these errors do not change the outcomes significantly.

For simplification, for the analysis of the indoor air temperature it was assumed that the living room and kitchen had about the same temperatures and therefore the mean of these two rooms was used for the analysis. This assumption is applicable for some dwellings, but it might be not true for dwellings. It is assumed that these errors do not change the outcomes significantly. Also, all indoor air temperature points taken during the whole day are taken into account in the analysis. However, the thermal sensation might be different during different times of the day. An analysis of the relation between indoor air temperature and thermal sensation for different times of the day may give insight in the magnitude of this effect.

The relation between indoor air temperature and thermal sensation was investigated. However, a better measure for assessing thermal comfort is the operative temperature which is derived from air temperature, mean radiant temperature and air velocity. In this study, mean radiant temperature and air speed were not measured, and thus the operative temperature could not be calculated and indoor air temperature was used instead in the analysis. This makes it difficult to compare the results of this study with the PMV model. Also the relatively low number of data points, especially in the upper and lower extremes of the thermal sensation scale, makes comparison between predicted and actual percentage of dissatisfied difficult. For example, Figures 4 and 5 show that the percentage dissatisfied in the category 'very cold' is lower than in the category 'cold', which is not expected. Furthermore, the relations between indoor air temperature and thermal sensation and between indoor air temperature and thermal preference were assessed without considering activities or metabolic rates of the residents. By considering activities or metabolic rates in the analyses, better insight in the relation between indoor air temperature and thermal comfort could be gained.

5. Conclusion

In this paper, the relationship between thermal comfort, resident behaviour and indoor air temperature was investigated. Significant relationships were found between thermal sensation and thermal preference, clothing level, metabolic activity level, activities related to thermal comfort taken in the last half hour, and indoor air temperature in the living room. A significant relation was also found between thermal sensation and indoor air temperature in the living room. In further research, the relation between thermal comfort perception and operational energy consumption and dwelling characteristics can be investigated to improve the knowledge on the relation of thermal comfort with energy consumption and energy saving in dwellings.

These data can be used to compare the comfort level registered by the residents with the comfort level predicted by the PMV model, and link this to the indoor climate and the energy consumption for heating. This information can help to understand the relations between user preferences, indoor climate and energy consumption for heating.

6. Acknowledgement

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The datasets generated during and/or analysed during the current study are not publicly available because of data agreements made in the OPSCHALER project, but can be made available after agreement with the authors on an individual basis.