Department for Energy Security & Net Zero

Infrared Heating

Investigations from literature and user experience tests

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Contents

Executive Summary

Proponents of infrared (IR) heating systems claim they have the potential to reduce domestic space heating demand through the provision of thermal comfort at lower background air temperatures. The majority of UK homes have gas boilers, which use radiators to deliver most of their heat via convection, heating the volume of air within a room. Conversely, rather than directly raising air temperature, IR heating systems deliver most heat directly onto surrounding surfaces, which includes the occupant. Thus, switching to IR heating may mean homes can be heated to lower background air temperatures and achieve energy savings.

This report presents an appraisal of the current understanding of IR heating systems in domestic heating contexts. This project uses a combination of literature reviews and user experience tests to identifies issues that require further investigation in any future field trial designed to quantify the impact of IR heating on energy use in homes.

Systematic and grey literature reviews suggest there is little existing research into the effectiveness of using infrared heating in domestic contexts, but modelling and limited field trials indicate benefits from IR heating can be gained under certain conditions. The literature suggests IR heating can be an affordable, easy-to-install option for small homes that meet current building standards, though there is little data collected in real-world conditions to support these claims.

The user experience trials conducted in this research yielded important data to complement existing knowledge. Specifically, the results indicated that occupants may not be comfortable if they are not positioned in line of sight, or relatively close to the IR emitter. Line of sight was the most important variable, and any future investigations should explore the likelihood that occupants will be able to achieve a direct line of sight of emitters in homes (e.g., how people move around homes, how much coverage emitters provide, the potential for obstructions, etc.). It is possible this effect is less pronounced in homes with higher levels of energy efficiency; however, it was not possible to investigate this in this project.

Users discussed how different heating systems features affected their comfort to identify what factors should be included in any future field trial, for instance perceptions of heat-up and cool-down times and the “feel” of heat from different IR heating systems (e.g., wallpaper vs. panel systems), from IR vs. gas boilers, wall vs. ceiling mounted IR systems, and modulating vs. standard controlled IR systems.

The investigations do not provide a definitive evaluation of IR heating in homes; 114 people experienced two 45-minute sessions of IR in a test chamber, which does not represent how they may respond to comfort in their own homes. However, the data highlights what issues should be considered in any large-scale field trial to establish if any energy savings can be achieved via IR heating systems.

For any future research or field trial, recommendations are provided on four elements: 1) the **type of homes** that should be included in a trial’s sample, 2) the **types of households** that

should be recruited, 3) the **IR system typologies** that should be investigated, and 4) the **type of data** that could be collected to generate more nationally representative information.

In summary, the main themes to consider that are uncovered by this research are:

- User behaviour post-IR installation may not result in lower background set points being selected by occupants, thereby removing the energy-saving mechanism for IR; longitudinal studies over multiple heating seasons may be needed to understand if lower heating set points are retained long term.
- Comfort provided by IR heaters is most sensitive to maintaining line of sight. Investigating the likelihood of achieving line of sight to IR emitters in real-world homes may provide the underlying potential for IR to be effectively installed in homes, to inform if an IR field trial is necessary.
- Comfort is exceptionally subjective and measuring comfort is extremely challenging and would be a complex addition to a field trial.
- Comparisons between IR system features (type of heater material, location of heater, heater controller) did not usually yield meaningfully different results. This indicates attempting to compare between IR system performance may not be practical and would require very large sample sizes.
- Unintended consequences of lower background air temperatures include increased surface condensation risks, which may need to be considered alongside technical performance in a field trial.

1 Introduction

1.1 Background and project aim

The UK is evaluating the role of alternative electric heating technologies in it's Warm Homes Plan. This report explores the potential effectiveness of one alternative heating system for UK homes: *infrared (IR) heating*.

IR, like all electrically powered heating systems, can be considered low carbon when powered by decarbonised electricity. Unlike heat pumps, which can produce approximately three kWh of heat for every one kWh of electricity they consume, IR panels can only produce one kWh of heat for every kWh of electricity they consume.

However, IR heating systems provide more of their heat to occupants via radiation, rather than convection (which radiators in homes use). Since radiant heat theoretically provides better levels of comfort to occupants, it is possible that homes with IR heating systems may be heated to lower background air temperatures, while still providing similar levels of comfort. This provides a possible energy-saving mechanism. This mechanism, however, relies on occupants feeling more comfortable when exposed to IR heating systems to the point that they will choose to make a behaviour change and reduce the set point temperatures in their homes.

Unintended consequences of using IR heating in homes are relatively unknown, for instance, a lowering background air temperature could potentially lead to lower surface temperatures and therefore increased condensation risk. Additionally, little is known about the extent to which occupants experience better comfort levels from IR heating systems or the likelihood that occupants would choose to heat their homes to lower background levels. This means there is little data to suggest if the energy-saving mechanism is likely to be achieved or what the magnitude of the savings may be. The IR heating industry claims that occupants achieve comfort at lower ambient room temperatures. More data outlining the effects of such lower room temperatures on the health and condition of the building fabric is required.

This research aims to investigate this energy-saving mechanism, by gathering data on the experience of users of different types of infrared heating.

1.2 Introduction to infrared heating

IR heating systems are designed to provide more of their heat via radiation than convection, directly raising the temperature of surfaces exposed to the IR heating device rather than needing to use air as a medium. A traditional example of this would be the immediate warmth one feels standing near an open fire, where the heat is primarily transferred via radiation from the hot flame to the person, as opposed to the more gradual heating of the air within the room and, subsequently, the occupants further away from the fire.

The high emissivity of human skin ($\varepsilon \approx 0.98$) makes it particularly receptive to IR radiation; therefore, IR heating systems may be more effective at providing comfort than other electric heaters that rely on convective heat transfer mechanisms, and thus have a potentially stronger mechanism for energy saving.

IR provides its radiation at wavelengths between visible light and microwaves, between 0.7 µm to 1.0 mm, which is a shorter wavelength range (i.e., stronger IR) than other direct electric heaters.

As per BS ISO 20473:2007, the electromagnetic spectrum is divided into several spectral bands as shown in Figure 1-1 below [2]. Radiant heating from the Sun is mostly IR-A (near) and IR-B (mid). IR heating systems within these ranges require very high temperature emitters (>1000°C) rendering them unsuitable for domestic applications.

Most IR domestic heating systems operate within the far IR spectral band (IR-C); as this has a lower energy intensity than shorter wavelengths, the heating panels require a larger surface area to radiate heat onto surfaces directly exposed to the heating panel as confirmed by previous market feasibility studies into IR heating systems for domestic space heating [3].

To qualify as IR rather than simply direct electric radiant heating systems, various thresholds for the proportion of heat being emitted by panels have been suggested, usually varying between 40% and 60% in the far IR wavelength band. This report does not attempt to validate or measure the amount of IR being emitted by different heating systems, nor does it attempt to define or recommend a threshold for IR heating.

Designation of the radiation		Short designation			Spectral bands[a] Wavelength λ nm	Frequency ν THz	Wavenumber σ cm^{-1}	Photon energy Q_e eV
Ultraviolet radiation	extreme UV	UV		EUV	1 to 100	3×10^5 to 3 000	10^7 to 10^5	1 240 to 12,4
	vacuum UV		UV-C	VUV	100 to 190	3 000 to 1 580	10^5 to 53 000	12,4 to 6,5
	deep UV			DUV	190 to 280	1 580 to 1 070	53 000 to 36 000	6,5 to 4,4
	mid UV		UV-B		280 to 315	1 070 to 950	36 000 to 32 000	4,4 to 3,9
	near UV		UV-A[b]		315 to 380	950 to 790	32 000 to 26 000	3,9 to 3,3
Visible radiation, light		VIS			380 to 780	790 to 385	26 000 to 13 000	3,3 to 1,6
Infrared radiation	near IR	IR	IR-A	NIR	780 to 1400	385 to 215	13 000 to 7 000	1,6 to 0,9
			IR-B		1 400 to 3 000	215 to 100	7 000 to 3 300	0,9 to 0,4
	mid IR		IR-C	MIR	3 000 to 50 000	100 to 6	3 300 to 200	0,4 to 0,025
	far IR			FIR	50 000 to 10^6	6 to 0,3	200 to 10	0,025 to 0,001

[a] The wavelength values are valid for delimitation of the spectral bands. The values for frequencies, wave numbers and photon energies are approximate values given for convenience.

[b] For other fields of application, which are excluded from the scope of this International Standard, there may be different definitions. For example, IEC 60050-845:1987, identical with CIE Publication No 17.4, for its purpose, defines the upper limit of the UV-A band as 400 nm (see also Annex A).

Figure 1-1: Spectral bands of the electromagnetic spectrum (Adapted from BS ISO 20473:2007 [2])

The British Standards Institute identified characteristics for emitters of infrared electro-heating for industrial applications in BS EN 60240-1:1994 [4], BS EN 60519-1:2020 [5] and BS EN 60519-12:2018 [6] focus on the safety of these IR heating installations; however, they are only applicable to industrial IR emitters with surface temperatures between 500°C and 3000°C, not for domestic space heating systems, where hazardous exposure is far less of a risk.

BS EN IEC 60675-3:2021 [7] sets the standards for lower temperature household infrared heaters with nominal radiation efficiency of 40% or higher, an emitter surface temperature between 40°C and 200°C, without visibly glowing parts and specifies a method for measurement of nominal radiation efficiency (a test chamber).

Radiation efficiency is defined in BS EN IEC 60675-2021 as the ‘ratio of heat flow into a test chamber by radiation exchange between an active radiant heating surface and the inner surfaces of the chamber to the nominal electric power of the heater inside the chamber’; the remaining proportion of electrical consumption still transfers heat to the chamber but by alternative heat transfer mechanisms.

However, this does not suggest any specific standards/guidelines for sizing and positioning of heaters in domestic settings. Safety for household IR devices has guidelines in BS EN 60335-2-53:2011 [8]; however, as household devices are far less hazardous than devices for industrial applications this is specifically for saunas and infrared cabins.

2 Method

Several research activities were undertaken to produce a body of evidence from which recommendations for any future IR heating field trial design could be made. These are shown in Figure 2-1. This section describes the methods of each of these research activities.

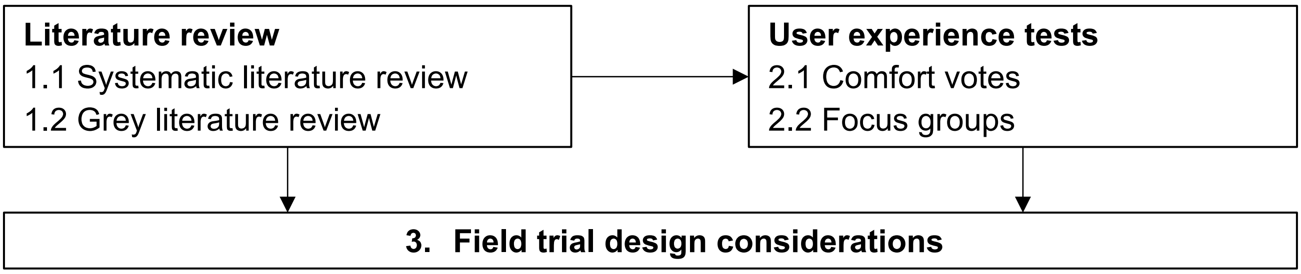

Figure 2-1 Research project overview

2.1 Approach to literature reviews

A systematic literature review was undertaken, supplemented by a focused traditional review of all academic and grey literature available. This was done to ensure that no types of literature were excluded from the review. Both literature reviews aimed to identify existing evidence on the effectiveness and efficiency, user experience, and environmental impacts of such systems to inform a bench test of technologies and potential future field trials.

Systematic literature reviews are a valuable tool for gaining a comprehensive understanding of a given subject. They involve gathering data from multiple sources, evaluating the findings, and drawing meaningful comparisons that can inform further research and knowledge production. Systematic literature reviews boast key advantages, such as their level of transparency, reproducibility, and ability to minimise bias. The advantages of systematic literature reviews help to pinpoint areas where there may be inconsistency or gaps in knowledge and suggest further investigation in these areas. This provides helpful information about what is currently known about a particular topic, which can guide future studies.

However, there are limitations to systematic literature reviews as well. Some of these include the potential for publication bias, the difficulty of comparing studies with different methodologies or scopes, and the risk of overlooking relevant grey literature, such as reports, conference proceedings, or unpublished research. To overcome these limitations, the traditional review was undertaken to capture additional grey literature from various sources, such as government and industry reports.

This approach ensured that a diverse range of perspectives and evidence was considered, providing a more comprehensive understanding of the infrared heating landscape in domestic contexts. Furthermore, the inclusion of grey literature helped to address potential gaps in the published literature, thereby contributing to a more robust and reliable review.

To conduct the systematic review, a search strategy was developed and applied across Scopus and Google Scholar, including screening for eligibility based on selection criteria. A full description of the review process is presented in the Appendix of this report. The traditional review undertook more general web searches and adopted convenience sampling and snowball sampling techniques.

2.1.1 Systematic review; keywords, exclusion criteria, and filtering

Keywords were selected to ensure a comprehensive and focused search of relevant literature. The keywords included "Infrared", "Infra-red", "IR", "heating", "home", "house", "dwelling", "domestic", "test", "trial", “thermal comfort” and “comfort”. These keywords were then combined using Boolean operators (AND, OR) to create targeted search queries.

To refine the search results and eliminate irrelevant papers, exclusion criteria were established. These included studies that focused on non-domestic applications of infrared heating in industrial or commercial settings, as well as papers primarily concerned with other heating technologies such as heat pumps, solar thermal, or gas heating systems.

A two-step filter process was used to identify relevant papers. The first step, title filtering, looked at the titles of search results and used keywords and focus of the study to determine which papers were directly related to the topic. The second step focused on abstracts, reading them carefully and evaluating them to determine relevance to the research context. Those papers that met the inclusion criteria, specifically that feedback from users had been collected as part of the research, and which showed alignment with the objectives of the research were retained.

2.2 User experience test design

The outcome of the literature review helped inform the IR bench trials conducted with users. These took place in the Salford Energy House (Figure 2-2): a replica Victorian solid wall end-terrace house constructed within an environmental chamber capable of replicating external air temperatures between -12°C and +30°C.

Figure 2-2 The Salford Energy House Facility

Environmental conditions in the chamber and conditioning void can be controlled which makes it possible to compare the comfort of occupants when exposed to different heating technologies with greater confidence and speed than houses in the field. In the IR user experience trials, the chamber was held constant at 5°C to ensure consistency when comparing different heating systems. IR heating systems were installed in the energy house in three test rooms. In addition, the Energy House has a conventional hydronic central heating system with radiators in each room that can be served by a domestic gas-condensing combination boiler. Infrared heating systems were installed in the energy house in accordance with the manufacturer's specifications, with participants maintaining line-of-sight exposure to the IR emitters throughout the user experience trials.

2.2.1 Energy house monitoring

Monitoring of the conditions inside the test home and in the external chamber was undertaken throughout the experiment. Sensors installed in the test rooms allowed the operative and air temperatures achieved in the room at different locations to be calculated, as well as allow for the energy provided to achieve these temperatures to be monitored at one-minute resolutions. Sensors included:

- Environmental chamber air temperature per minute
- Centre room air and black globe temperature per minute
- Room corners air and black globe temperature at low, mid, and high heights per minute
- Energy consumption of each heating system per minute

2.2.2 Research questions (RQ)

The experimental setup was designed to answer the following research questions:

RQ1 Does the location of the occupant relative to the heat emitter affect perceptions of comfort?

RQ2 Does the mounting location (wall, ceiling or coving) of the IR heat emitter affect perceptions of comfort?

RQ3 Does the type of heat emitter affect perceptions of comfort?

RQ4 What is the time to perceived comfort after switching on IR heating?

RQ5 What is the time to perceived discomfort after switching off IR heating?

RQ6 What are participants' general perceptions of IR heating as alternative central heating systems for their homes?

2.2.3 Experimental design

114 participants took part in the user experience trials, sourced via a market research fieldwork agency. Each participant received a £75 incentive payment. Participants were given a description of the study by a researcher and provided with an information sheet. After the opportunity to ask questions about the research, they provided written informed consent.

Participants were randomly allocated to experience different heating systems in the Energy House and were asked to use voting buttons to describe their comfort during the trial, as well as participate in a focus group to discuss their experiences with social scientist researchers.

The trial was conducted over 10 days, with a maximum of 12 participants per day. Two sessions were performed each day, with six participants in the morning session and six in the afternoon session. Each session was further split into two 45-minute tests. Participants were grouped into pairs and each pair experienced two rooms with different heating conditions.

The experimental design, shown in Table 2-1, explored how user comfort and experience were affected by the following variables, (plus a final test was included to provide a comparison against a control gas boiler group in week three):

- IR heater location (ceiling, wall, coving)
- User seating location (optimised by distance and line of sight)
- Five IR heater types (described in Section 2.3)
- Standard and modulating controller

Table 2-1 IR user experience experimental design

Room	Week 1 & 2 variables	Week 3 variables
A	IR technology 1 (ceiling mounted) Standard control 4 seat positions	IR technology 1 (wall mounted) Modulating control Gas boiler comparison
B	IR technology 2 (wall mounted) Standard control 4 seat positions	IR technology 1 (wall mounted) Standard control Gas boiler comparison
C	IR technology 3 (wall mounted) IR technology 4 (coving mounted) IR technology 5 (ceiling mounted) Standard control	IR technology 4 (coving mounted) IR technology 5 (ceiling mounted) Heating system (gas boiler & radiators) Standard control

During the 45-minute testing period, the heating schedules were replicated such that each participant had identical conditions on which to base their comfort perceptions; these are shown in Table 2-2. In weeks 1 and 2, Rooms A and B had a different setup to Room C since they were also used to investigate how occupant seating position affects comfort. In week 3, all rooms had an identical heating schedule and only the heater types were being compared.

Table 2-2 Weeks 1 & 2 Heating schedule (Red = heat up from 15°C to 21°C, Yellow = hold at 21°C, Blue = heaters turned off) and Seat position (1-4)

Minutes	5	10	15	20	25	30	35	40	45
Room A	1	1	1	2	3	4	1	1	1
Room B	1	1	1	2	3	4	1	1	1
Room C	1	1	1	1	1	1	1	1	1

Table 2-3 Week 3 Heating schedule (Red = heat up from 15°C to 21°C, Yellow = hold at 21°C, Blue = heaters turned off) and Seat position (1-4)

Minutes	5	10	15	20	25	30	35	40	45
Rooms A, B & C	1	1	1	1	1	1	1	1	1

The four seating locations tested in weeks 1 and 2 in Rooms A and B were designed to replicate the best and worst seating locations to investigate how this would affect comfort, as shown in Figure 2-3. Where possible these timings were achieved, however, they may not be exact in all tests, some variation may be expected due to testers being unable to adjust the tests punctually.

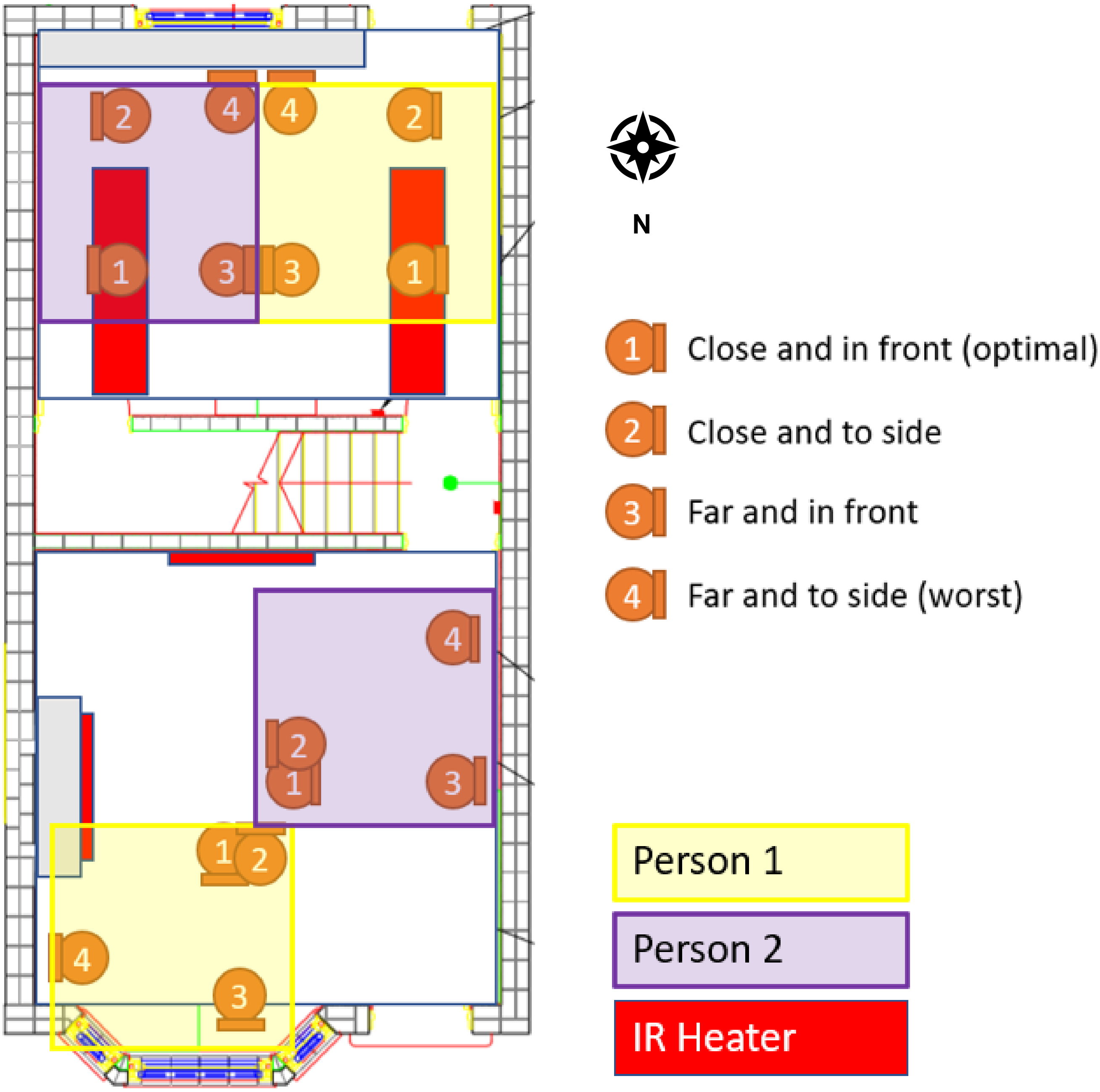

Figure 2-3 Seating positions in rooms A (top) and B (bottom)

2.2.4 Comfort voting method

During each experimental period, each participant was given a Button Box voting device (Figure 2-4). The Button Box is a remote data collection tool for thermal comfort research, with physical buttons connected to a datalogger that return a tactile response and audible click when pressed, to register the vote has been recorded. Each button corresponds to a point on the thermal scale.

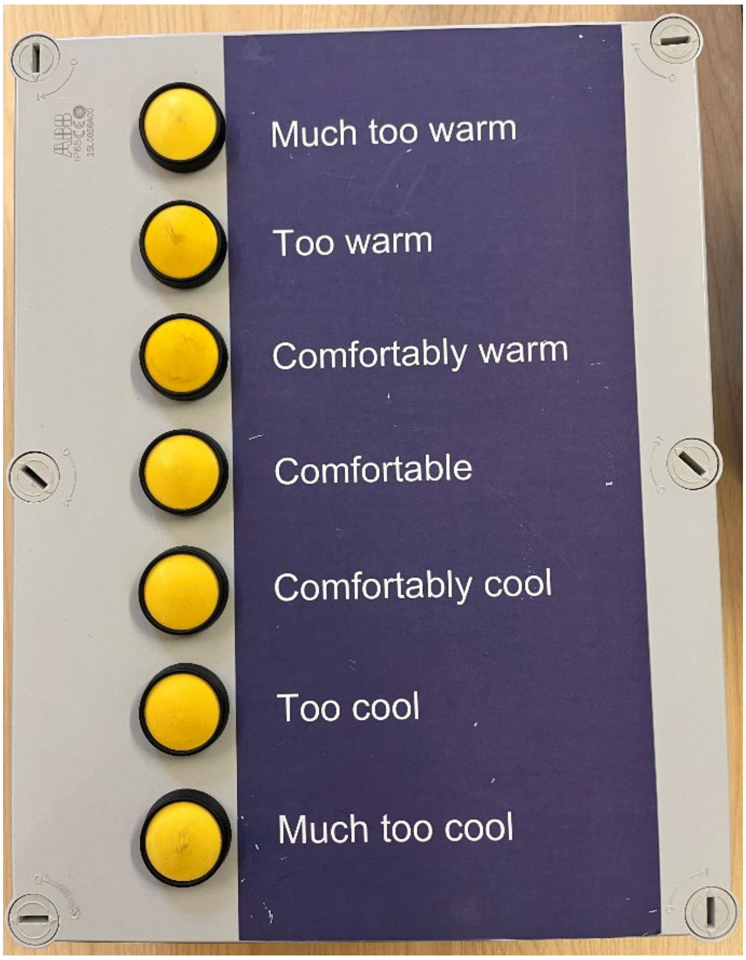

Figure 2-4 Button Box voting device

Thermal perception was measured using the Bedford scale [9], which combines notions of sensation and comfort. The Bedford scale is favoured in comfort studies due to its construction that allows the participant to indicate thermal acceptance (comfort/discomfort) and state (warm/cool) on a single scale. The scale is symmetrical, with a central point of 'comfortable' extending to thermal states of 'much too cool' and 'much too warm' at its ends.

Participants were instructed to press the button that most closely corresponded with their thermal perception at 1-minute intervals throughout the experiment. These data were then collated for all participants across all experimental stages to evaluate the time taken to achieve and lose a comfortable thermal state during warm-up and cool-down periods, together with the more general analysis of overall comfort between test phases.

Analysis of the votes at different room temperatures was undertaken to identify any statistically significant trends or correlated data that provided insights into the research questions.

2.2.5 Focus group method

Focus groups took place directly following the comfort perception experiment. Participants were reminded of the purpose of the focus groups, and they were given the opportunity to ask questions. Each focus group lasted half an hour and was audio-recorded. Discussions explored:

- What participants liked and disliked about the heaters.
- Any preference for the different heaters, and reasons for any preferences.
- Sensation of heat and how it compares to the heaters in their home.
- Perceptions of how quickly the heaters warm them up.
- How position relative to the heaters affected experience of heat, and preferred seating position.
- Whether and why participants would use infrared heaters in their home as their only heat source and as an additional heat source.

Audio recordings were transcribed verbatim and the transcripts were analysed thematically [10] using the research question: “What were participants’ experiences of the infrared heaters?” NVivo 12 was used to code and organise the data.

2.3 Selection of IR heating systems

All heat emitters transfer heat using all three modes of heat transfer (convection, conduction, and radiation). IR heaters transfer a large proportion of their heat through radiation i.e., emitting energy through electromagnetic waves in the infrared region between 0.75 μm to 100 μm (Bergman et al., 2011):

- Short wave or Near IR (NIR) (0.75 μm to 1.4 μm)
- Medium wave IR or Mid IR (MIR) (1.4 μm to 3.0 μm)
- Long wave IR or Far IR (FIR) (3.0 μm to 100 μm)

Generally, shorter (NIR) wavelengths emit a larger proportion of heat as IR depending on the nature (physical properties) and temperature of the emitting surface (Bergman et al., 2011).

IR Heaters therefore can have varying properties in terms of their wavelength and the proportion of heat being emitted as IR. This information is not always provided by manufacturers; however, the emitter surface temperature can to some extent be used as a proxy to determine if the heater sits in the near, mid, or far IR range.

Other differences include the material used to make the emitter, the size and shape of the emitters as well as where it is located in a room, and how it is controlled. These differences can be used to categorise different archetypes of the emitter, though different types share similar attributes.

A full description of the IR heater typologies can be seen in the Appendices of this report. A summary of the different types of IR heaters available and their salient attributes is shown in Table 2-4.

Table 2-4 Overview of IR heater typologies and salient features

IR type	IR Range	Emitter surface temperature	Filament temperature	Power output	Element material	Application
A	Near (0.78 to 1.4 µm)	500°C to 900°C	1,800°C to 2,600°C	1 kW to 1000s kW	Halogen & carbon fibre	Non-domestic
B	Mid (1.6 to 2.0 µm)	< 900°C	1,000°C to 1,500°C	Min 750 W	Halogen & carbon fibre	Non-domestic
C	Mid & Far (1.5 to 8.0 µm)	Mid: < 750°C Far: < 120°C	Mid: 1000°C Far: 300°C	Min 50 W	Carbon fibre & resistance coils	Mid: Non-domestic Far: Limited domestic
D	Mid & Far (2.0 to 10.0 µm)	Mid: < 1000°C Far: < 120°C	Mid: 1000°C Far: 300°C	Min 150 W	Ceramic	Mid: Non-domestic Far: Limited domestic
E	Far (3.0 to 15.0 µm)	60°C to 300°C	< 300°C	200 W to 3 kW	Carbon crystal, & fibre, Aluminium, Stainless steel	Domestic & Portable
F	Far (8.0 to 15.0 µm)	< 65°C exposed < 31°C embedded	< 90°C	< 450 W	Graphite or Grafoil, Graphene film	Domestic; on or embedded in building fabric

In addition to the IR heaters in Table 2-4, *conductive heaters* or electric "mat" heaters are commonly embedded into the building fabric of homes, for instance in electric underfloor heating. These heaters heat the building fabric which then becomes the emitter. These are conductive heaters and are not usually considered IR heaters, so were excluded from these tests, but they share similar properties as Type F IR heaters.

In the user experience tests in this study, only domestic heaters that are available for householders to purchase were considered, i.e., Types A, B, C, and D IR heaters were excluded. Six IR emitters in total were selected from Type E and F to take forward to the user experience tests.

The choice of emitters was selected to allow comparison of a range of characteristics:

Table 2-5 IR emitters selected for user experience tests

IR heater	IR Type	Measured emitter temp	Installed power output (W)	Emitter surface area (m^2)	Controller	Element material	Location
1	E	110 °C	1950	1.68 m^2	On / off	Aluminium, powder-coated	Room B Wall
2[i]	E	90 °C	1640	1.36 m^2	On / off	Aluminium, powder-coated	Room A Ceiling
3[ii]	E	87 °C	1650	1.08 m^2	Modulating	Glass	Room A Wall
4	E	85 °C	1005	1.01 m^2	On / off	Aluminium alloy	Room C Wall
5	E	150 °C[iii]	670	0.36 m^2	On / off	Aluminium, powder-coated	Room C Ceiling (corners)
6	F	50 °C	1540	7 m^2 film spread across ~12 m^2 ceiling	On / off	Film behind plasterboard, plaster skim & paint	Room C Ceiling

Images of the IR heating technology installed are shown in Figure 2-5 to Figure 2-9.

Figure 2-5 IR Heater type 1 installed in Room B

[i] Same as Heater 1 except ceiling mounted
[ii] Same as Heater 1 except with modulating controller
[iii] Emitter situated behind plasterboard

Figure 2-6 IR Heater type 2 installed in Room A

Figure 2-7 IR Heater type 4 installed in Room C

Figure 2-8 IR Heater type 5 to be installed in Room C

Figure 2-9 IR Heater type 6 installed in Room C (mid-install left, covered pre-plaster right)

3 Results

3.1 Literature review

3.1.1 Systematic literature review

The findings from the systematic literature review are presented in the Appendix of this report. Following the keyword searches and filters applied, seven relevant papers were selected when using Scopus while a further ten papers were identified when using Google Scholar. A summary of the relevant findings is presented here:

- The use of infrared panels is recommended only in buildings with high levels of energy efficiency and with lower thermostat setpoint temperatures. Also, mid-terraced houses are more suitable for application than detached houses [11].
- Results indicate that despite a lower indoor temperature, residents can achieve comfort by using localised “personal” heating, and a significant energy-saving potential was found [12].
- Savings of up to 50% when replacing electric floor heating or night storage heating with infrared heating were observed [13].
- IR panel heating systems do not match heat pump performances in terms of energy consumption yet can be an affordable option for smaller apartments [14] on a life cycle cost basis where space heating demand is relatively low, since they may be cheaper to install and maintain.
- Research found good overall comfort levels from the IR-panel system; however, existing methodologies may overlook certain discomforts related to the proximity and sheltering of heaters [14].
- Infrared panels are easier to fit in than underfloor heating systems, and more suitable for rooms where residents only stay for a short time [15].

3.1.2 Grey literature review

A description of the grey literature is presented in the appendix. An additional eleven papers were identified in the Appendix 7.3 of this report. Below is a concise overview of findings from one particularly relevant report on highly efficient residential buildings [16]:

- Average internal surface temperatures are slightly higher with Infrared (IR) heating than underfloor heating, but only when the heating surfaces of the IR heaters are included. Without including the IR heater surfaces the actual average surface temperatures are lower.
- Indoor ambient air temperatures in IR heated rooms can be 0.6°C cooler to achieve the same comfort outcome, reducing ventilation losses.

- IR has a good ability to respond quickly to part load requirements and consumes 2-15% less energy than underfloor heating depending on heat pump (HP) operation and control strategy.
- IR has 50% lower transfer losses compared to underfloor due to its lower heat loss into building structures, thermal inertia, and better controllability.
- Radiant efficiency of models ranges from 40-70%, which depends on insulation at the back of modules as well as position in the room; ceiling-mounted produces the highest efficiency while wall mounted could be improved upon.
- To maintain a constant internal room temperature, it was found that radiant panel heaters consumed 2.9 times more electricity than an HP system, 3 times when taking experimental design conditions into account, though this varies based on install quality.
- User surveys showed residents find infrared systems thermally comfortable and easy to operate; pairing them with Solar PV for life cycle costs makes them significantly cheaper over 50 years compared with air source heat pumps.

Salient findings across the rest of the grey literature and manufacturer documentation include:

- Following links and references from press articles and product literature reports of claimed product performance which could not be verified objectively. I.e., manufacturer's claims of "healthier air" or "reduced stratification" appeared to apply results or findings to domestic situations with no available data to back up these claims [17].
- Most of the IR panels described in the reports have 40 to 70% radiant efficiency, with the remaining 30 to 60% of heat given out via alternative heat transfer mechanisms. It was not possible to identify any differences between outcomes linked to IR heating systems with a different radiant efficiency [16].
- Satisfaction and performance assessments described tend to be for IR panels as one component of multiple interventions or supplemental heat provision to other low-carbon heating systems rather than exclusively IR heating systems. This makes it challenging to attribute benefits to IR heating in isolation from other variables [17].
- One field trial from the Hebridean Housing Partnership, [18] describes the installation and subsequent early removal of IR systems in 95 properties in 2015 due to tenant complaints. The report describes monitoring and user surveys in 2022 and found 75% of tenants unhappy with their IR heating systems, finding them expensive to run and unable to provide adequate comfort, compared with 13% dissatisfaction with air source heat pump systems and 14% dissatisfaction with gas boiler systems. Residents also complained about poor installation and the IR heating systems are being replaced with air source heat pump heating, to improve comfort levels for tenants, meet EESSH targets, and maximise available funding.

3.1.3 Literature review implications for future research

This review identifies key findings on infrared heating from economic considerations to data gaps, which could inform any future research:

- **Economic Implications**: IR heating panels, recognised for their low capital cost, low maintenance, and potential longevity, could be a cost-effective choice despite their elevated energy consumption and operational costs compared with heat pumps.
- **Suitability of IR Panels**: With their compact design and no requirement for pipework, IR panels demonstrate suitability for smaller homes, mid-terraced houses, without wet central heating systems, and which adhere to or exceed current building regulations. Also, they appear appropriate for infrequently used homes or those with fewer occupants.
- **Hybrid Systems**: The literature reveals numerous instances advocating a hybrid strategy, which combines IR panels with alternative heating solutions like heat pumps, underfloor heating, and solar thermal panels; allowing rapid heat delivery to augment a slower launching low-energy heating system. This approach seems to enhance both energy efficiency and comfort, making it a promising area to explore.
- **Thermal Comfort Predictions**: The current practice involves using the ASHRAE-55 adaptive model to anticipate thermal comfort in IR heating scenarios. While this method generally yields satisfactory comfort levels, there's a possibility that it might not capture certain uncomfortable conditions. Hence, evaluating the ASHRAE-55 model's reliability could be explored via IR heating field trials.
- **ASHRAE-55 Model and Human Body Representation**: The model takes into account multiple parameters including clothing insulation and metabolic rate to gauge comfort levels. However, the simplistic representation of the human body as a small plane surface may not fully capture the human thermal perception. Therefore, field trials could potentially explore more accurate methods of depicting the human body within thermal comfort models.
- **Shading and Angle of Incidence**: Literature shows that radiative heat transfer relies on direct exposure to the heat source; surfaces that are not directly facing an IR emitter will not receive IR heating. Also, the greatest intensity of IR emissions will be directly in front of the heating panel. The potential for discomfort in shaded areas or areas not directly facing IR panels (e.g., behind furniture or room corners) should be investigated.
- **Surface Temperature Moisture Risk**: Literature has focused on the comfort of occupants without considering that intermittent usage, lower ambient air temperatures, and reduced convectional air circulation may increase the potential for surface moisture and mould formation. Particular areas of concern are known thermal bridges which are shaded from direct IR emissions (e.g., ground floor perimeters behind furniture or installed units, inside cupboards). Any future research or field trial should collect data on these risks and possibly include modelling to evaluate risks.

- **Humidity and Airborne Water**: Increased humidity levels alter the performance characteristics of IR as water droplets in the air absorb a significant proportion of mid and far IR radiation, reducing the heating potential of exposed surfaces at increasing distances. Comparisons of IR systems performance at different levels of humidity, and in kitchens and bathrooms, should be investigated.
- **Room Surface Coverings**: Different surface coverings have different emissivity to IR radiation so will heat up, store, and re-emit heat at different rates (e.g., carpeted *vs.* tiled floors). The literature has not provided information on the impact this may have on comfort when using IR heating. A field trial could investigate differences in IR heating performance in high and low-exposed thermal mass homes to compare how these perform and also investigate if internal wall insulation reflects more IR and improves performance.
- **Heat Loads**: It is unclear how IR heater sizing and positioning are determined, and modelling approaches used by manufacturers may not be fully validated. This makes it difficult to directly compare IR heating systems even where specifications are similar.
- **Occupancy typologies**: Literature has identified IR heating provides maximum comfort when users are in front of panels with no obstructions. It does not consider how this requirement affects comfort levels for different occupant archetypes who use homes in different ways.
- **Hot water heating:** The literature tends not to provide information on the provision of secondary heating in homes when IR systems are installed, and if this affects overall householder energy bills, e.g., switching from gas to an electric hot water system.
- **Data Gaps**: There is a significant lack of field trial data on IR heating and systems such as underfloor heating and electric panels which may offer similar benefits to IR. Any future field trials should specifically assess whether lower indoor temperatures from a range of products can deliver comfort.

3.2 User experience tests: Comfort votes

This section outlines the findings from the evaluation of the data collected during the experiments in the test house. Of the target 120 participants, 114 were successfully recruited. The comfort votes of each participant (entered into the button box machines during their time in the experimental chamber) were time stamped and plotted to understand how comfort changed over the experiment duration and reacted to changing variables. Comfort votes were then correlated to the air and operative temperatures in the chamber to investigate the research questions listed in Section 2.2.2.

Table 2-2 shows the full experimental procedure for weeks 1 and 2 in rooms A and B, which may be summarised as a 15-minute heat-up period in a fixed seating position, a 15-minute period of sustained temperature where the occupant moves seat position at 5-minute intervals, and a 15-minute cool-down period in a fixed seating position.

This section provides an overview of the approach taken to analyse comfort voting and specifically answers research questions 1 to 5 previously identified in Section 2.2.2. It is important to note that the conclusions that can be made from the comfort voting preferences often varied from the participant experience data collected via focus groups, undertaken immediately after the test sessions. This highlights that comfort preferences are complex, and caution is required when interpreting comfort data collected via a single method.

RQ1 Does the location of the occupant relative to the heat emitter affect perceptions of comfort?

During weeks 1 and 2, seating locations in rooms A and B were modified to assess the impact of different heater technology and installation positions on occupants' comfort (Figure 2-3). To analyse this, a linear mixed-effects model (LMM) approach was used to evaluate the null hypothesis in each room:

- H_0: There is no difference between seat positions in relation to comfort levels

The participant vote was the dependent variable, and the seat location and operative temperature were both independent variables. The LMM models determine the statistical significance of the effects. A 95% confidence level (p-value of 0.05, two-tailed) was considered to reject the null hypothesis. Care must be taken in interpreting the results since comfort is a subjective concept, only a relatively small sample of participants were included in these tests, so the results may not be representative of the wider population.

For room A which had ceiling-mounted panels, the test results show a significant difference between position 1 (near and facing) and seat positions 2 (near but not facing), and 4 (far and not facing), but no difference with position 3 (far and facing). This could indicate that being in line of sight (facing) the emitter is more important than being close to the emitter. However, the ceiling mounted panels provided relatively broad coverage of the room, since the room was relatively small, i.e., seat position 3 was still relatively close to the emitter’s coverage, as can be seen in Figure 2-3, which may account for why position 3 was not significantly less comfortable than position 1.

In room B with wall mounted panels, there was a significant difference between seat location 1 and all the other locations. This may indicate that wall mounted emitters do not provide as broad coverage as ceiling mounted emitters. The geometry of the rooms was different which may be affecting the results, i.e., being further away from the emitters and more easily out of the line of sight of the heat emitters in Room B. However, the manufacturer recommended panel systems (power and positions) were used, so the results should be relatively robust.

In summary, occupants may not be comfortable if they are not positioned in line of sight, or relatively close to the IR emitter. To illustrate this visually, Figure 3-1 shows the distribution of comfort votes for all participants each minute for the duration of the test in Room B during Weeks 1 and 2.

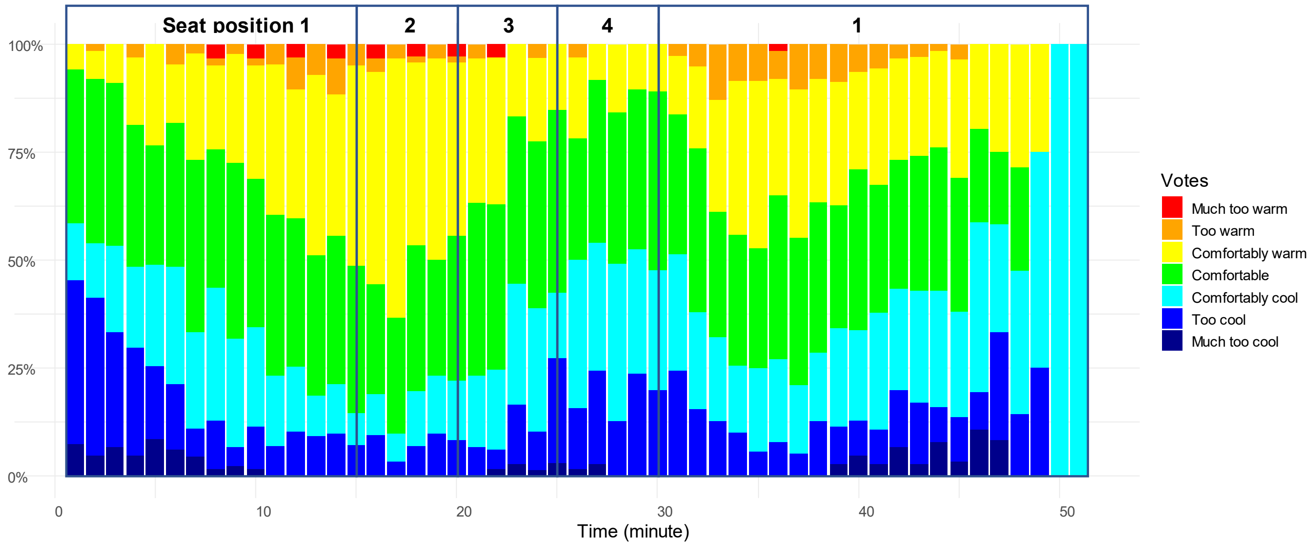

Figure 3-1 Average comfort votes Room B (wall panels), Weeks 1 & 2

As can be seen, over 50% were already in the “Comfortably Cool” to Comfortably Warm” range when the experiment started, indicating a perception of thermal comfort. As may be expected, there were also a substantial number of “Too Cool” and “Much too Cool” votes (approximately 40%) indicating cold thermal discomfort, as the starting temperature was between 15°C and 17°C.

During the first 15 minutes of testing, where the IR system was turned on and began to heat up, the proportion of participants indicating cold thermal discomfort reduced, being replaced by more “Comfortably Warm” votes. This indicates a degree of warming up or improving comfort. However, due to the high proportion of reported comfort at the beginning of the experiment, there was insufficient initial discomfort to accurately evaluate the time taken to reach comfort.

During the middle 15-minute period, when the participants initially vacated the optimum seat position 1 (close to and facing the IR panel) and moved to seat position 2 (close to, but facing away from the IR panel), the trend of increasing “Comfortably Warm” votes appears to reverse after a few minutes lag. This indicates participants are less comfortable if they are not facing the IR panel heaters, even if they are still close to the panels. Also, there was a significant difference ($p < .05$) in comfort votes at this stage compared to seat position 1.

As the occupants then move to seat position 3 (facing, but far away from the IR panels) after 20 minutes, the proportion of “Comfortably Warm” votes diminishes further, indicating proximity to the IR heaters is possibly more important to comfort than directly facing the heaters. Again, there was a significant difference ($p < .05$) in comfort votes at this stage compared to seat position 1.

After 25 minutes the occupants move to seat position 4 (far away and not facing the panels) and the proportion of “Too Cool” votes remains high and there are almost no “Too Warm” votes. This was consistently the least comfortable seat position in the tests and was found to be significantly ($p < .05$) less comfortable than seat position 1.

After 30 minutes the participants moved back to seat position 1, and the proportion of cold thermal discomfort votes decreased to be replaced by votes in the three comfortable categories, but also some “Too Warm” votes. This is particularly interesting, given that after 30 minutes the IR device is turned off and enters the cool-down phase. This suggests that the IR panel retains sufficient heat to improve comfort for around a further 5 minutes and that being close to and directly facing the IR heater may be necessary for comfort to be achieved.

After 5 minutes of the cool-down phase (35 minutes total) the trend reverses and the proportion of cold discomfort increases until the experiment's conclusion. The proportion of “Too Cool” votes increased, but not significantly, meaning the time to discomfort could not be calculated from the data.

These results suggest that for wall mounted IR systems, IR heaters may not provide comfort when occupants are not directly facing and close to heaters.

This is important, since it is likely that there will be occasions in homes, especially in rooms with unusual shapes, and when people are moving around homes, that these conditions will not be met. This implies comfort may be achieved intermittently in homes with IR heating, depending on the occupants’ activity and room dimensions. Having intermittent comfort will impact the likelihood that an occupant may be willing to reduce their home’s set point temperature. If this does not happen, IR heating may not be able to achieve energy savings in homes.

Figure 3-2 shows that in Room A in Weeks 1 & 2, which was equipped with ceiling mounted IR heaters, perceived comfort was also affected by the location of occupants relative to the emitter, though the effect was less strong, indicating that they may provide more uniform heating to occupants than wall panels, though this may be due to the experimental set up in the rooms being more favourable. The magnitude of the impact of seat locations, heat emitter choice, and other findings are discussed in the following sections.

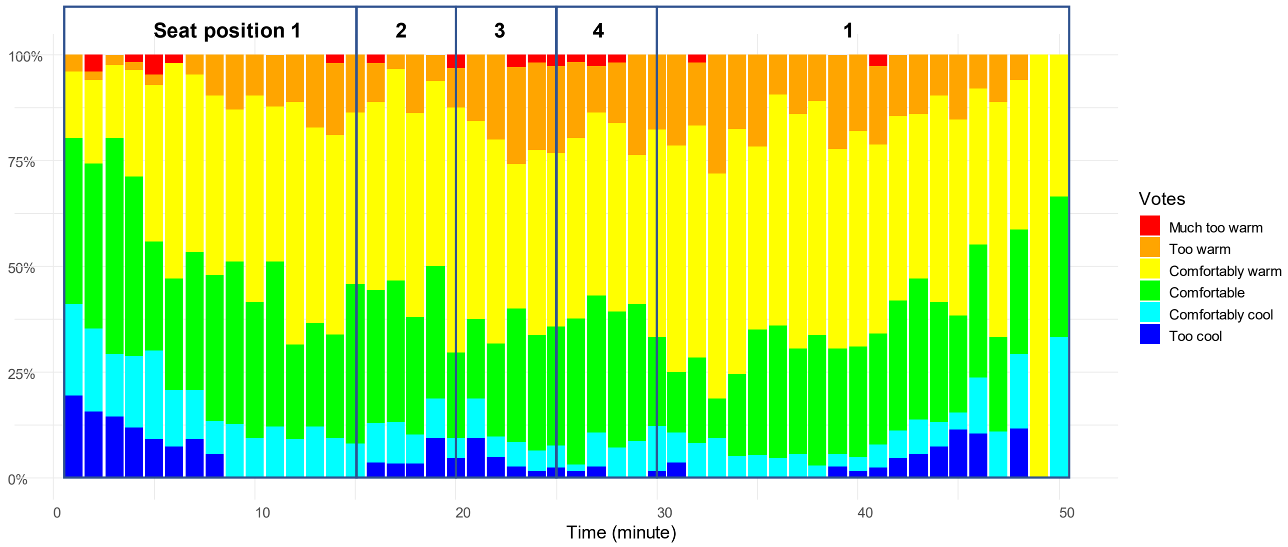

Figure 3-2 Average comfort votes Room A (ceiling panels), Weeks 1 & 2

RQ2 Does the mounting location (wall, ceiling or coving) of the IR heat emitter affect perceptions of comfort? and, RQ3 Does the type of heat emitter affect perceptions of comfort?

The following section outlines a series of statistical analyses undertaken to explore discrete comparisons between different IR heating options which combined answer research questions 2 and 3. It must be noted however that although these tests may identify trends in the data, the comfort votes as a methodology are relatively novel, meaning there is not a good understanding of their robustness in the sample size that is relatively small, meaning they may not be representative of the broader population.

Ceiling vs. wall mounted panels

Comfort votes in room A were compared to votes in room B, during weeks 1 and 2, to compare the effects of mounting identical panels on the wall or the ceiling. The results indicate there was no significant difference in comfort depending on where the panel was mounted.

Modulator controller vs. standard controller

In room A, comfort votes in weeks 1 & 2 were compared to votes in week 3 to compare the effects of using modulating (wall) versus non-modulating (ceiling) IR panels. The results indicate there was no significant difference in comfort as the result of using different controllers (i.e., modulating vs. standard).

Wall vs. coving vs. embedded ceiling IR emitters

In room C, comfort votes in all weeks were compared to evaluate the effect of different IR technologies. These emitters were made of different materials and mounted in different locations (wall, coving, and embedded ceiling emitters). The comfort votes suggested that the occupants were significantly ($p < .05$) less comfortable using coving compared to wall panels and embedded ceiling emitters. However, there was no significant difference between wall panels and embedded ceiling emitters.

Gas boiler vs. IR emitters
In week 3, in rooms A and B, participants were exposed to two identical sessions: one with IR heating panels and the other with gas boiler and radiators. In room A, a modulating wall panel was used and when the comfort votes were compared there was no significant difference between the IR panels and the gas boiler and radiators. In room B, a standard on-off wall panel was used, and again the comfort achieved by the IR panels were not significantly different from gas boilers and radiators.

In room C three different IR emitters were compared over all three weeks along with a single week of gas boiler and radiators. These emitters were made of different materials and mounted in different locations meaning the cause for any difference may relate to a combination of the emitter location and product. The comfort votes suggested that there was no significant difference in the comfort perception of participants between any of the emitters and the gas boiler and radiators.

Type E vs. Type F IR emitters
Comparisons between the Type E aluminium ceiling mounted panels in Room B could be compared to the Type F embedded ceiling emitter in Room C. This in an imperfect comparison as the rooms and occupants were different. However, initial data shows the comfort votes were different for these types of emitters. It is not clear that any one emitter was more or less comfortable than the other, just that the comfort votes followed a different pattern. This means that Type E might provide more comfort some of the time and Type F may provide more comfort at other times, I.e., they influence comfort differently. Additionally, the focus group feedback did not support the view that there was any difference between the emitter types, indicating more investigation is needed.

The findings from all these analyses are specific to this experiment and cannot be generalised for the wider population.

RQ4 What is the time to perceived comfort after switching on IR heating?

This section discusses the findings relating to the speed of response of IR heating and how this affects the time it takes occupants to achieve comfort. The tests were designed such that the occupant was “uncomfortably cool” (according to the Bedford scale) when entering the test house and to allow the first 15 minutes of their session to be devoted to heating up. The time taken for the participants’ vote to switch to any of the “comfortable” votes, was then recorded. This is plotted in Figure 3-3**,** with a shorter time taken to comfort being optimal. The most important finding is that because most people were comfortable at the outset of the test, there was limited detectable difference between the heat-up times of the different technologies, however, there was observable variability in the range of performance.

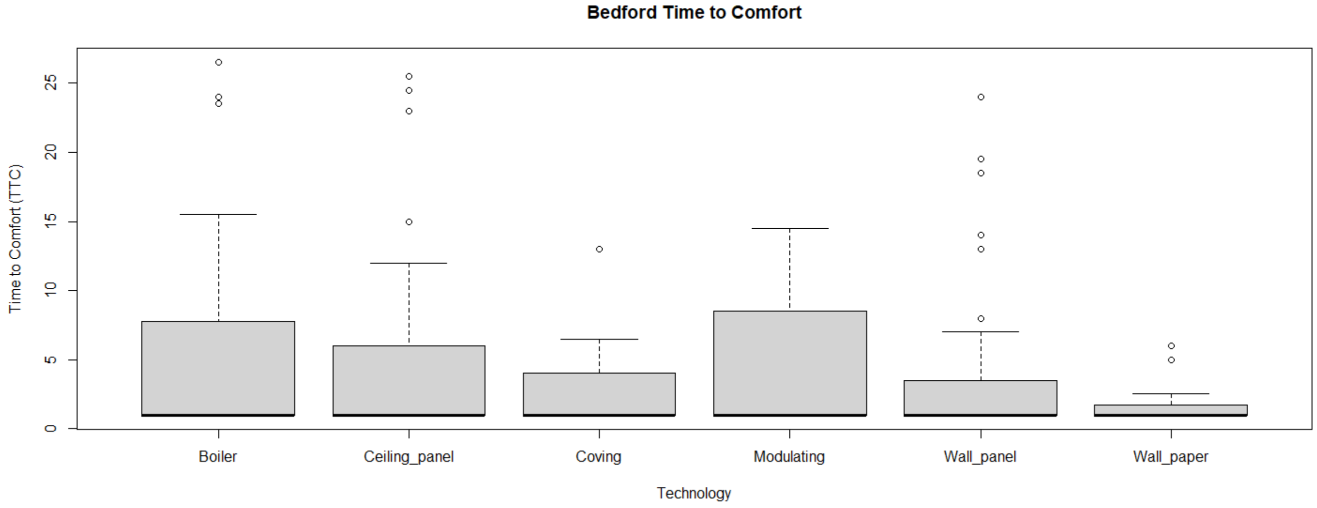

Figure 3-3 Perceived time to comfort based on Bedford scale

Although this appears to show that the wallpaper was substantially more effective at achieving comfort more quickly than the other heater technologies the results may be misleading due to the variability in the test conditions and the small number of votes that were recorded in each session. Out of the 114 participants, there was only a total of 204 valid individual time to comfort voting sessions (each participant took part in two sessions; however, some participants did not vote, or their votes were not recorded successfully during the first 15 minutes). This means that the sample size is too small to be able to generalise the results; a larger field trial would be required for this.

As mentioned, it was found that the starting temperature in the test house was perceived by most people as being already comfortable. Generally, all the emitters were effective in achieving comfort within the first 15-minute period, and on only 10 occasions did it take more than 15 minutes for participants to reach a state of comfort. Two participants did not reach a state of comfort at all throughout the entire experiment.

Thermal perception was measured using the Bedford scale [9], which combines notions of sensation and comfort. The Bedford scale is favoured in comfort studies due to its construction that allows the participant to indicate thermal acceptance (comfort/discomfort) and state (warm/cool) on a single scale. As participants were using the Bedford scale for comfort for the first time without an extensive introduction to how their votes would be interpreted, there may have been variability in the participants' interpretation of the Bedford scales.

To explore this possibility, a secondary analysis was made. This time all votes other than "Comfortable" were considered as expressions of discomfort, aligning with the Predicted Mean Vote comfort scale that considers discomfort as a departure from thermal neutrality [19]. Consequently, a new "Central" scale with only three votes, namely, Cold, Comfortable, and Hot, was developed. Figure 3-4 illustrates the impact of this modification on the time taken by the occupants to reach perceived comfort, with a shorter time taken to comfort being optimal.

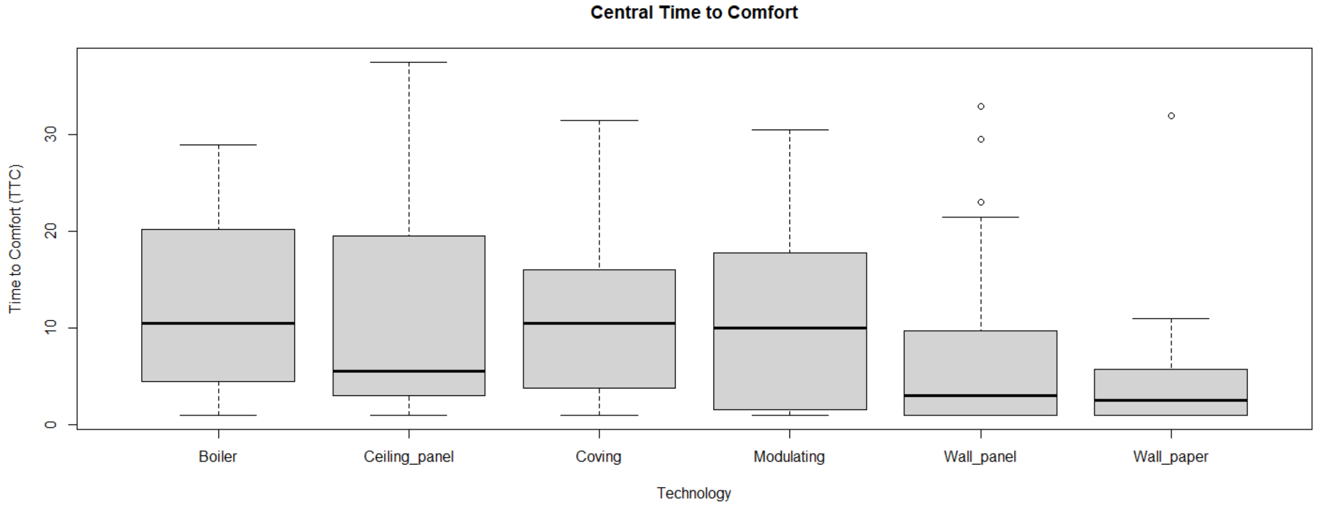

Figure 3-4 Perceived time to comfort based on Central scale

According to the Central scale, there were 52 instances where participants reported feeling comfortable at the start of the experiment, and 131 instances where participants expressed discomfort. As can be seen, wallpaper again appears to have a shorter time to comfort, though the emitter types are more similar.

There were 37 instances where it took more than 15 minutes for participants to achieve comfort, though on 146 occasions participants reached comfort within 15 minutes. Interestingly, 21 participants did not experience a state of comfort at any point throughout the entire experiment according to this revised assessment.

An additional complication is that the starting air temperature between the test sessions could not be perfectly controlled (due to the tests being undertaken in the energy house laboratory in quick succession) and so this may be affecting the point at which participants were expressing comfort. This is shown in Table 3-1.

Table 3-1 Average starting air temperature values for each technology

	Boiler	Ceiling Panel	Coving	Modulating wall panel	Wall panel	Wallpaper
Average air temperature (at the start of the test)	16	16	16	18	17	17
Average air temperature (during first 15 minutes)	17	17	17	19	18	17

A final complication may be that the participants entered the test house after walking through the environmental chamber, which was held at 5°C. This short journey may have biased the occupant's perceptions of comfort since the home, even though air temperatures lower than are conventionally found in homes, was relatively warmer than the immediate cold experience of the environmental chamber.

RQ5 What is the time to perceived discomfort after switching off IR heating?

This section explores the findings related to the duration it takes for occupants to experience discomfort after turning off the IR heaters. The experiments were conducted while occupants were in a state of "comfort" according to the Bedford scale. The last 15 minutes of their session were designated for cooling down. The point at which participants' votes transitioned to any of the "uncomfortable" choices after switching off heaters was recorded and visualised in Figure 3-5, with a longer time taken to discomfort being optimal.

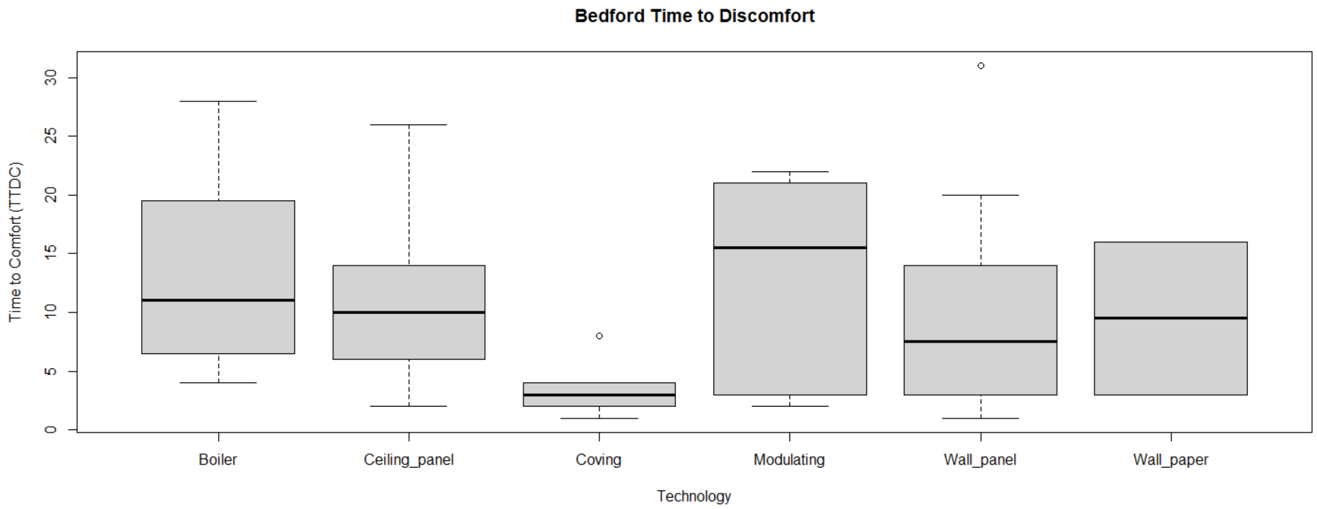

Figure 3-5 Perceived time to discomfort based on Bedford scale

Although the data suggests that coving was notably less effective in sustaining comfort compared to other heater technologies, these results might be misleading due to the variability in test conditions and the limited number of votes collected in each session. Among the 114 participants, there were a total of 204 valid individual voting sessions for time to discomfort (each participant took part in two sessions; however, some participants did not vote, or their votes were not recorded successfully in the last 15 minutes). Due to this limited sample size, the results cannot be generalised.

On only 2 instances did participants express discomfort and on 202 occasions they remained comfortable right after switching off the heaters. As can be observed in Table 3-2, the average air temperatures during the last 15 minutes of the experiment after switching off the heaters are similar for different technologies. Generally, all the IR heaters were effective in providing comfort within the last 15-minute period after switching off the heaters. On only 50 occasions did it take less than 15 minutes for participants to reach a state of discomfort while on 12 occasions it took more than 15 minutes for participants to reach a state of discomfort and on 142 occasions participants did not reach a state of discomfort at all.

According to the Central scale (Figure 3-6), there were 9 instances where participants reported feeling uncomfortable after switching off the heaters and 114 instances where participants expressed comfort. As can be seen, in the Central scale, wallpaper appears to have a shorter time to discomfort. Additionally, the time to discomfort exceeded 15 minutes on only 15 occasions, whereas on 108 occasions, participants experienced discomfort within 15 minutes or less. Interestingly, 81 participants did not experience a state of discomfort after the heaters were switched off throughout the end of the experiment according to this revised assessment. More research on the novel use of live comfort voting is needed to explore how respondents are interpreting the comfort scales and if the methodology can provide robust results.

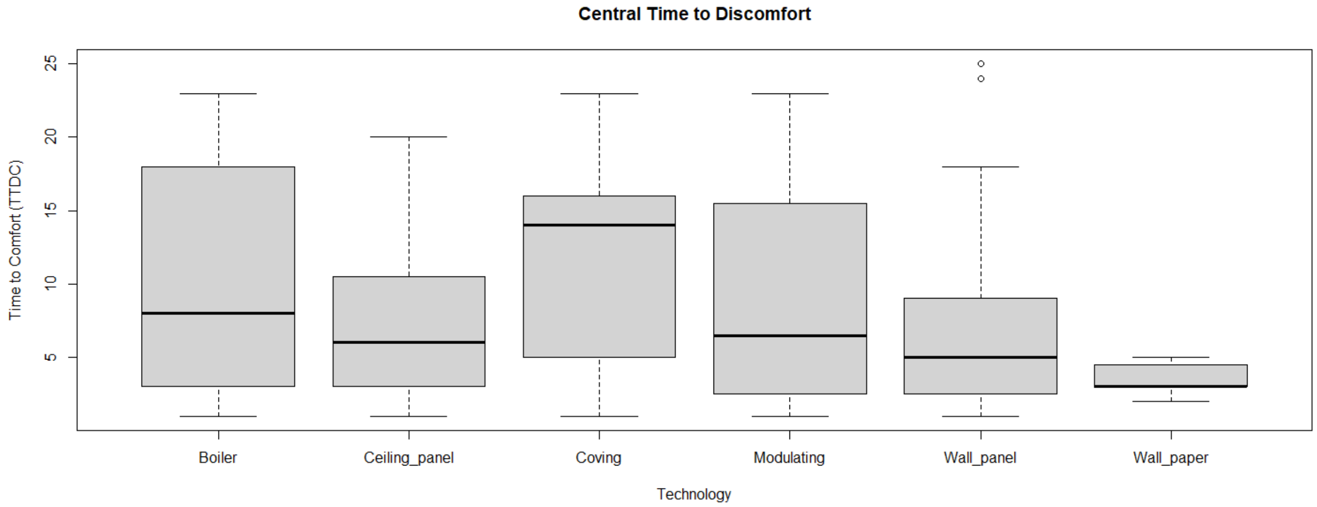

Figure 3-6 Perceived time to discomfort based on Central scale

Table 3-2 Average air temperature values for each technology after switching off the heaters

	Boiler	Ceiling Panel	Coving	Modulating wall panel	Wall panel	Wall paper
Average air temperature (at the time of switching off the heaters)	18	19	17	19	20	18
Average air temperature (during the last 15 minutes)	19	19	18	19	19	18

3.2.1 Additional observations: Surface condensation risks

This section focuses on analysing the air temperature in the room corners to investigate if different heaters lead to cold surfaces in the rooms. For this purpose, the average air temperature from measurements in the room corners (mean of high, mid, and low sensor heights) vs. centre of the room at mid height is plotted for each emitter type in Figure 3-7.

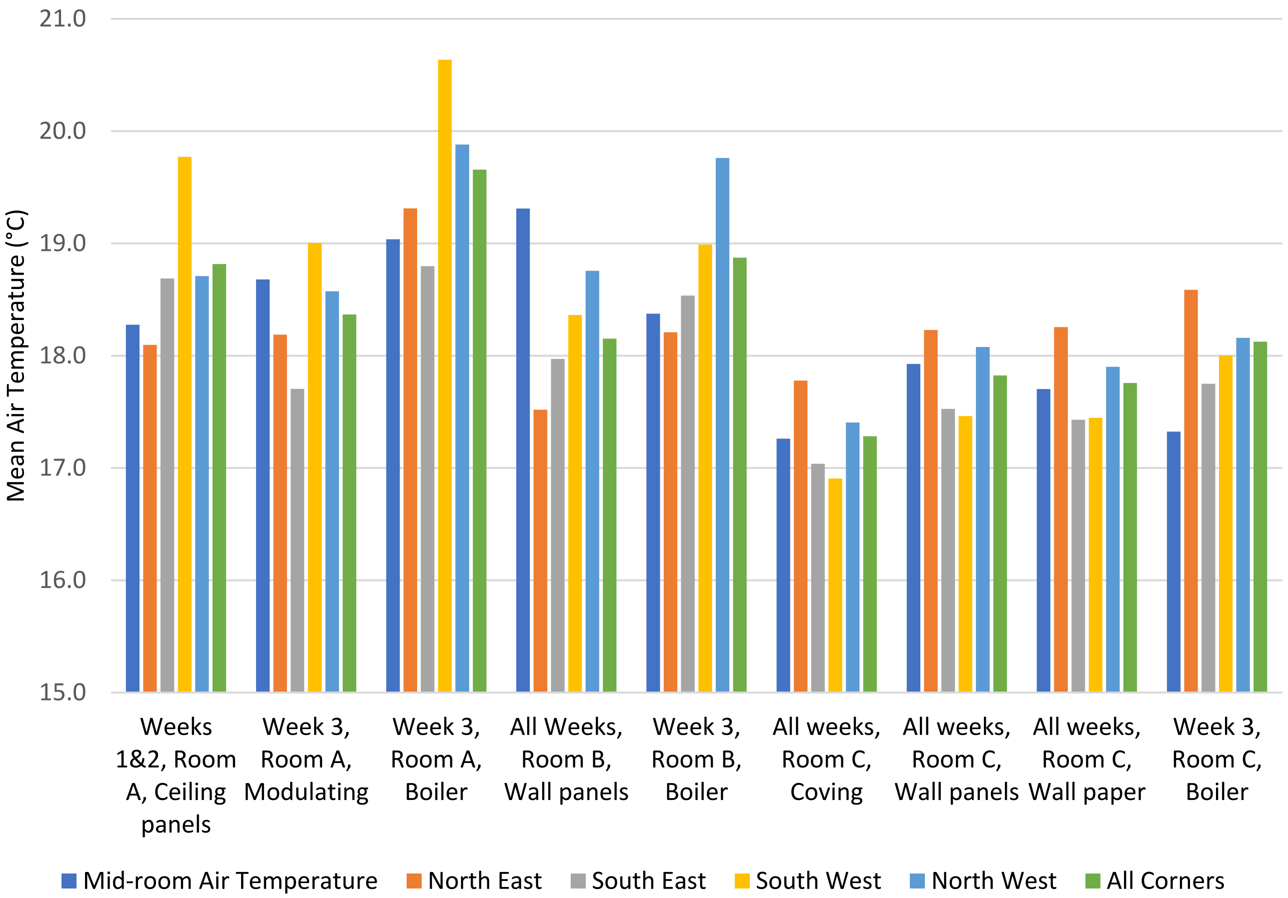

Figure 3-7 Average air temperature versus corner temperature for each heater

As depicted in Figure 3-7, there is not a significant difference in the air temperatures between the centre of the room or the corners at the mid-height (1.1m) of the room. There is some variability, for instance in Rooms A and B the room corners further from the emitters reported the lowest temperatures, however, these were also adjacent to external and stairwell doors where air exchange may have affected the temperatures reported. Additionally, the gas boilers had similar variability as observed by the IR emitters. However, these results cannot be generalised since they are specific to the room geometry, and experimental design used.

In summary, the tests cannot confirm if there will be an increase in surface condensation risks if homes were to switch to IR heating systems.

3.2.2 Summary of user experience tests

Several investigations have taken place during the experiment in the test home in order to provide data to answer five of the six research questions. A summary of these is presented in Table 3-3.

Table 3-3 Summary of findings from IR user experience tests

RQ	Null Hypothesis	Test	Result
1	Comfort is the same at all seat locations	Compare votes in seats 1, 2, 3 & 4 (Room A & B, Weeks 1 & 2)	Occupants may not be comfortable if they are not positioned in line of sight, or relatively close, to the IR emitter, with a significant difference in comfort observed (p =.05)
2	Comfort is the same if the IR heater is ceiling or wall mounted	Compare votes in Rooms A vs. B (Weeks 1 & 2)	There was no significant difference in comfort depending on if the panel was mounted on the wall or the ceiling (p =.05)
3	Comfort is the same if the IR heater is controlled using either modulating or standard controllers	Compare votes in Rooms A vs. B (Week 3)	There was no significant difference in comfort depending on the controller type (p =.05)
3	Comfort is the same regardless of the IR heat emitter	Compare average test comfort votes (Room C, all weeks)	Occupants were less comfortable using coving compared to wall panels and embedded ceiling emitters. There was no difference between different wall panels.
3	Comfort is the same regardless of the IR type	Compare average test comfort votes (Ceiling mounted Room C & Ceiling mounted Room A)	There was some difference (p = .05) between the embedded (Type F) and panel (Type E) IR ceiling emitters however not enough data to infer which was preferable just that there was a difference in the voting patterns.
3	IR heaters provide the same level of comfort as boilers	Compare average test comfort votes (All rooms, all weeks)	The tests could not identify a difference in comfort achieved between boiler and IR heaters
4	Time to comfort is the same for gas wet central heating (radiators) and IR	Identify change in comfort during the first 15 mins (All rooms, all weeks)	Occupants reported to be comfortable on entering the test house, no time to comfort could be calculated.
5	Time to discomfort is the same for gas wet central heating (radiators) and IR	Identify change in comfort votes during the last 15[iv] mins (All rooms, all weeks)	Occupants reported being comfortable for the entire 15[iv]-min cool down, no time to discomfort could be calculated

[iv] In some instances, the cool down session may have lasted up to 20 mins

3.2.3 Test house experiments key findings for any future research

Considerations for a field trial design based on the user experience tests include:

- Line of sight or proximity to the wall IR heaters appear to affect comfort and should be considered in a field trial.
- Coving was potentially providing less comfort than wall and ceiling emitters. Ceiling mounted emitters did not appear to achieve any greater comfort than wall mounting emitters. However, mounting location affects the potential for IR emitters to be out of the line of sight, which does affect comfort. Additionally, this finding may be affected by test rooms and the IR setup (mounting locations, low ceilings, small rooms, etc.) in this experiment. Given the apparent influence of proximity to the IR heater, it follows that sensor mounting location may have more significance for larger rooms or rooms with higher ceilings and could therefore be further explored in a field trial.
- Controller type ("on / off" versus modulating) was not found to have a difference in comfort levels and so may be less important to consider as a variable during a larger field trial.

3.3 User experience tests: Focus groups

This section addressed the final research question:

RQ6: What are participants' general perceptions of IR heating as alternative central heating systems for their homes

To answer this required qualitative data collection from the participants, which was provided by focus groups after the test house experiments had ended.

From these, we identified four themes in the data.

1) Infrared thermal comfort is about participants' experiences of the heat generated, including how warm they felt, how this changed based on their position relative to the heaters, and how warm the room felt.

2) Heater design is about their perceptions of the appearance and use of the heaters.

3) Using infrared heaters in your home is about the factors that would influence their decision about adopting the heaters.

4) Approach to heating your home includes their discussions about how they currently operate their home heating and how infrared heaters might fit with their approach.

These themes and their constituent sub-themes are described below.

3.3.1 Infrared thermal comfort

This theme is about participants' experiences of the heat provided by the heaters. It comprises five subthemes that cover the sensation of warmth from infrared heating, the amount of heat provided, the sensation of only some parts of their body feeling warm, their comparisons of the different types of heaters and different positions of the heaters in the rooms, and how thermal comfort varied with their position relative to the heaters.

The sensation of infrared heat
Participants talked about how the infrared heat felt gentle on their skin, and they contrasted it with previous experiences with infrared patio heaters, which they described as being fiercer and less pleasant.

> *"I think it's better than the patio heaters that you get that you've seen outside in beer gardens and things because that seems to melt your face. This wasn't doing that. It was more of a friendly heat." (Week 1, day 1, pm)*

> *"There was a good feel with heat coming from them." (Week 1, day 3, am)*

While some noted that the heat generated wasn't warm enough to feel pleasant on their skin, others specifically liked that the heat felt gentle and that there weren't large swings in temperature when the heaters were switched on and off.

A few participants talked about infrared heating bringing health benefits because they associated infrared with medical therapeutic devices, or they thought that keeping the air temperature in their home a little lower than they would normally do would mean they are less likely to feel congested from dry air and perhaps less likely to catch colds.

> *"I feel the heat's healthier that comes from the infrared, to be honest with you. It's not dry, is it? It's not dry heat. You know when you have your heating on, it always turns it on at night-time. At our house, it's almost tropical sometimes. You also get that, when you're abroad and with air-conditioning and that type of thing, if you put that on at night-time you end up with colds, don't you, in summer." (Week 2, day 1, am)*

(In)sufficient heat

Participants talked about the amount of warmth the heaters generated, and whether they felt warm enough in the different rooms. Many felt cold throughout the different conditions, and regardless of what temperature the room was heated to, or where they were sitting, they remained cold. Despite participants wearing layers of clothing, some talked about how they wanted a blanket or extra layers to keep warm. Partly, this may have been because participants described the house as very draughty and noted how much of the heat was lost from the doors and windows.

> *"We were very, very cold. I think we all felt the same way and we're still cold right now." (Week 1, day 1, am)*

> *"I was like, oh my goodness, it's so cold … right?" (Week 1, day 1, am)*

In contrast, others talked about how they had felt comfortable throughout, and despite the rooms heating up and cooling down, they had not felt too hot or too cold.

> *"I was never uncomfortably cold or uncomfortably hot in there. It was just a nice consistent kind of heat for me. I was okay. I didn't feel uncomfortable at all in terms of the heat or cold. I was just steady Eddie all the way through." (Week 1, day 1, pm)*

Differences are, to a certain extent, likely to be due to personal preference, with some participants discussing how they prefer a much warmer temperature than others in their family. Some talked about how they generally feel the cold so it takes a lot to warm them up.

> *"If I had the choice in that room I would have definitely turned it up more. Definitely. I prefer to be comfortably warm, not comfortably cool. I was still comfortable and cool, but I would prefer to be warm, comfortably warm." (Week 1, day 3, am)*

> *"I think for me, they just weren't warm enough. I like to be really warm and cosy and I just don't think they were warm enough for me." (Week 1, day 2 pm)*

> *"I just felt it was not warm enough for me. But I do take a lot to get warm." (Week 1, day 1, pm)*

Although participants were generally not satisfied with the overall comfort delivered by the IR heaters, most participants reported that the heaters were quick to warm up to their operating temperature. However, some talked about how they would take too long to warm the whole house to a sufficient temperature.

"I think they were quite quick to heat up. Obviously, it were quite cold when we first went in, but within a few minutes, you could feel the room getting warmer." (Week 1, day 4, am)

"When you come in from a long day you need something [that provides heat] a lot more quickly. I want to turn my heating on and I warm up straight away. Whereas this, I feel like it would take time to warm up." (Week 2, day 3, am)

Comparing conditions

Participants discussed their experiences of the heaters in the different rooms, and for the panel heaters, whether they were positioned on the walls or the ceiling. There was no consistent preference for the type of heater or for positioning the panel heaters.

Many simply couldn't tell the difference between the different heater types. Some preferred ceiling-mounted heaters as they thought they heated more of the room, whereas others preferred wall-mounted as they thought they provided more heat.

"The heat just felt very similar all the way through to me, so comfortable." (Week 1, day 4, pm)

I preferred the heaters on the side than up above. I thought it seemed to heat better than it did coming down. (Week 1, day 4, pm)

In the second room it did seem as though it were a bit more comfortable because the heat was above and coming down. (Week 2, day 1, am)

I was colder in the one with them on the wall overall I would say. Probably because you can feel it more on your head. (Week 1, day 1, pm)

Several participants commented that it seems counter-intuitive to position heaters on the ceiling, as heat rises, so a lot of the heat would be lost. One participant wondered whether this could lead to a psychological effect of not feeling warm enough.

"What's strange is that obviously the ceiling ones, the ones on the ceiling, when you think about it logically in your head, it's like, well heat rises, so they are no good up there because it's just going back up. It's not getting to my feet. Psychologically, in your head is, do you think my feet are not warm." (Week 1, day 3, am)

While relatively few participants experienced the wallpaper and the coving heaters, where people expressed a preference, they preferred the panel heaters. Some talked about the coving heaters providing a more patchy heat, but not everybody who experienced these heaters thought so: some did not notice any difference between the heaters.

"I felt like the ceiling was a bit more sort of spread around, you could sort of feel the coving one in patches, if that makes sense, I don't know if it's designed to do that, but you could sort of feel a bit of warmth coming and then just cool off. Whereas when you had that one on the ceiling coming down, that just was a steady heat all the way through." (Week 1, day 4, pm)

"I found it slightly, I wouldn't say much of a difference, but slightly warmer with the

panels [than the wallpaper]". (Week 2, day 2, am)

There was no clear difference in heating experience based on how the panels were controlled with participants unable to tell the difference between the different types of controllers.

Position relative to the heaters

Rather than the type of heater or controller, what appeared to make the biggest difference was where participants were positioned relative to the heaters, and whether participants were sitting near a door or window, where they could feel the draughts from outside.

During the experiment, participants experienced heat from the panel heaters when they were sat closer and further away from the heaters, and when they were directly in front of them and offset laterally.

There was a clear effect of distance, with participants feeling warmer when they were close to the heater, and much cooler when they were sat further away. This provided the sensation that the heaters weren't warming the whole room.

"And when they were near, they were very warm." (Week 1, day 4, pm)

The exception was when they were in the centre of the room and could feel the heat from several panels at the same time. Some, but not all, of the participants reported this position as comfortable.

"When I was near them, it was comfortable, but the temperature dropped when I got near the window. But when you got in the middle, it was just about right." (Week 1, day 3, pm)

However, even when sitting near and directly in front of the heaters, several participants noted that the panels were positioned too high on the wall so that they warmed their faces but not their bodies (see 1.1.5).

"I didn't really feel much benefit from them until I stood up, and when I stood up and I got the sense that they were on and I could feel a bit warmer, but when I was sat down at this level, I couldn't feel a great deal." (Week 2, day 1, am)

"It would have been nice further down on the walls, I think. Whether it was just a placebo or what, it just felt as if it was almost going over the top of me, the heat. Like I wasn't catching it." (Week 1, day 3, am)

3.3.2 Heater design

Participants talked about the design of the infrared heaters and we identified two themes in the data: their appearance, and the position of the heaters in the room.

Appearance

Participants liked the slimline design of the panel heaters and how it takes up relatively little space in the room; less room than radiators.

> *"I liked how slimline they were, not jutting out too much." (Week 1, day 3, am)*

> *"They do look nicer than the normal radiators. They're not as bulky are they, they're neater looking." (Week 1, day 1, am)*

Some also talked about liking the printed design on the panels themselves, while others liked how they blended into the background.

> *"I liked the design, how it was incorporated into the aesthetics of the room because ours were the picture ones on the wall. So it wasn't like just a big bulky heater in the corner. You couldn't really tell it was there." (Week 1, day 4, am)*

> *"We had heaters with pictures on, beautiful scenery. So that was fantastic. And compared to an ugly radiator, I thought having that in your house was amazing." (Week 2, day 3, pm)*

> *"What did I like about the heaters? They were quite invisible, some of them. You could make them invisible." (Week 1, day 3, am)*

> *"I liked the look of the heater to be honest with you because it looked quite discreet." (Week 2, day 1, am)*

Some participants, who had not seen the panel heater with pictures on, talked about how it might be possible to display artwork on them. A few were interested in being able to display their photos on the heaters.

> *"It's quite plain-looking and I was even coming up with suggestions saying you could have a work of art on there as well. A piece of art as well as being a heater would probably be better than a plain white thing on your wall." (Week 1, day 3, am)*

They also like that the heaters are powered electrically and so don't require pipework. They talked about how this could provide a much clearer and cleaner look to their rooms. A less cluttered space was also a benefit of the ceiling-mounted heaters.

> *"I think the one thing that I like about the system is, depending on how well you can get it wired in, would be the fact that it'd leave your living space nice and clean. Clean aesthetically, as in no radiators there. So if you had it on a ceiling and it was effective, nobody has anything on the ceiling really, do they, apart from some form of lighting." (Week 1, day 3, am)*

However, a few participants who experienced the coving heaters noted that the coving in their home is a character feature and they would not want to replace it with coving heaters.

> *"A Victorian terraced and I like the coving that I've got. Like to put something up there would it look an eyesore." (Week 2, day 1, pm)*

Positioning

Participants talked about how the wall heaters were not positioned in a convenient place, as they were at a level where television screens and pictures would normally be.

> *"You've got painting on the walls and TVs on walls and you'd be competing where to put them and things like that all the time." (Week 1, day 1, am)*

> *"They're a bit of an eyesore for me, especially the first room because it's where most people would put a TV to be honest." (28th pm)*

For this reason, several participants preferred a ceiling or coving heater. However, others talked about how they could not believe that a ceiling-mounted panel would heat the room as effectively as a floor-based one, as they thought that heat rises and so a heater on the ceiling would not heat the space below very well. They thought that the convenience of having the heaters out of the way on the ceiling did not compensate for having a cold floor.

> *"I liked the fact that the heaters were on the ceiling. In the modern environment, and the way houses have been made, it gave you a bit more room for furniture and things like that." (Week 1, day 2, am)*
> *"The ones in coving were good. You might as well have the heater there, leave your wall free." (Week 1, day 4, pm)*

A few suggested that positioning them in the coving or ceiling makes them safer as people are less likely to touch them.

> *"They're up and out the way. You're not going to touch them by accident, or anything like that." (Week 2 day 3, pm)*

Participants also commented that the wall heaters were positioned too high as they could feel warmth mainly on their faces rather than on the rest of their bodies. They talked about how they might feel warmer if the heaters had been positioned lower on the wall.

3.3.3 Using infrared heaters in your home

This theme is about the factors that would influence participants' decisions about adopting the heaters in their own homes. It comprises five sub-themes: cost; control over the heat; suitability in different homes and rooms; supplementary heating; and sustainability.

Cost

Cost was the area that participants talked most frequently about when discussing whether they would be interested in using the heaters in their own homes. For the majority, cost was the most important factor in their decision and included the cost to purchase and install the heaters, the cost to run them, and the cost to maintain them. The potential maintenance cost was a concern to some who had experienced the infrared heaters inside the walls as they assumed repairs would be expensive.

> *"If it was cheap enough to purchase, cheap enough to buy, cheap enough to install and cheap enough to run, then yes, it's a viable option for some people." (Week 1, day 1, am)*

> *"I think the initial cost, if you change from gas to infrared, how much is it going to cost, and again, how much is it going to run? Because that's the most important, and also the maintenance, if anything goes wrong, especially if you have a wall. No disrespect, but if you had a wall, would you have to get into the wall if something went wrong? (Week 2, day 1, am)*

In order to seriously consider changing to infrared heaters, they would want them to be significantly cheaper to run than their gas central heating. Some participants discussed how much cheaper they would expect infrared heaters to be, and figures from 10% to 50% cheaper were suggested.

> *"If it was more cost-effective then you'd probably think, you know what, it might be worth it. We'll have to go with it and manage it. But if it's just as expensive as normal heating them I probably wouldn't bother." (Week 1, day 1, pm)*

> *"If you save 50% on your heating then I'd have them everywhere." (Week 1, day 1, pm)*

A few of the participants highlighted that a move to infrared heating might require a better insulated home so that the cost of installing insulation would need to be considered when calculating whether they are financially attractive.

> *"I think it would come down to cost as well. Because if you were looking at introducing infrared into homes would that go hand-in-hand with insulation and all other parts of the package? And who's responsible for that cost? Is it the homeowner, is it grants board. It's a bigger picture, isn't it?" (Week 2, day 2, am)*

Control

The temperature control provided by the heaters was also important. Participants perceived a major potential benefit to be that it is easy to turn heaters off, enabling different rooms to be kept at different temperatures. They noted that while it's possible to turn radiators in different rooms off, it seems more difficult than simply unplugging an electric heater.

> *"Because obviously, it's electric, so you can plug it in and unplug it. So, if someone's saying, that room's too hot, you could probably manage it a little bit easier than going to turn your radiators off because no-one's sat in that room." (Week 1, day 3, am)*

They talked about how it would be useful to be able to programme the heaters to individually turn on and off at different times, therefore allowing them to give better differential control of the heating in different parts of their home.

> *"If we could do it so you're only heating the room you need to heat. So at night time, if it's really cold, like at this moment, you can have the radiators on upstairs, and the heating on upstairs, at a low level, so it's comfortable. Just take the edge off the chill. And leave the rest of the house alone. And then, have that kick in when people start to get up. So I can see a use case for it in our house, because a lot of the time, a lot of the house is unoccupied." (Week 2, day 3, pm)*

They discussed that the heaters seem to warm up quickly, which makes it more feasible to turn them on and off as each room is being used. They also talked about how this instant heat makes the heaters more suitable to turn on for a short period, as they don't need to wait for radiators across the house to heat up, as is the case for gas central heating.

> *"If my heating is on an hour before I feel the benefit of it, I've wasted an hour of energy, and we said that, didn't we? And if it came on straight away like that, I'd only need it for a short period. And therefore it would be more cost-efficient because I've not wasted that hour where nothing has happened." (Week 1, day 4, pm)*

It also makes them more flexible than electric storage heaters, which often need to have been turned on the previous day in order to work, and sometimes cool down too quickly.

> *"Better than storage heaters, because once you put storage heater on, it heats up at night and then it uses it all. It might not last through the day, but they're probably more economical than a storage heater. So, for them that's got all-electric I think they're perfect." (Week 2, day 3, am)*

However, not all participants were convinced that the heaters would generate sufficient heat. They wanted control to be able to extend to the amount of heat generated as well as how quickly it is generated.

> *"Does it get warmer than what it was in that room? Can it go to like whatever temperature you want? (Week 3, day 3, pm)*

Suitability in different rooms and homes

Participants talked about how the heaters are better suited to smaller rooms rather than larger ones, as they might not generate enough heat for a large room.

> *"I'd probably just use it in the kids' rooms and the smaller rooms. I wouldn't use it in my living room or anything like that because it's quite open-plan so I think I'd just lose a lot of heat in that." (Week 2, day 1, am)*

> *"Probably handy especially in the bathroom in winter around about 3 o'clock in the morning when you desperately need a wee. But yes, definitely in a small room, I think it would work really efficiently, but in a bigger room, I think it would get lost in that space." (Week 2, day 2, am)*

They also thought the heaters are more suited to newer rather than older homes, as newer homes tend to have smaller rooms and better insulation.

> *"I'm in an oldish house - 1950s build. I don't think it would be good for my house…. Are you putting them in newer builds? It would probably work: the rooms are smaller. It might work a bit better than in my house." (Week 2, day 2, am)*

Supplementary heating

Many of the participants were interested in using infrared heaters as a supplementary heat source, keeping their existing heating and using the infrared heaters as required to top up the heat in some rooms or to heat just one room when heating in the rest of the home is not required. They discussed how they might be useful in rooms that get particularly cold, such as attic rooms or conservatories where it could be turned on as required.

> *"In certain rooms, I can have it. I was hoping to use in my attic. It's cold up there so I'd want one then on the wall. And you were saying about your conservatory." (Week 2, day 2, am)*

They also talked about using portable infrared heaters that they could plug in and position directly in front of them to provide instant heat. Several talked about how they would use this type of heater instead of the electric fires they currently use as a supplementary heater.

> *"If you were going to get one, it would be nice to have one right in front of you. I'd like a little portable one next to yourself." (Week 1, day 3, am)*

> *"So, if you could take out the electric fire because I think that in itself uses a bit of energy, but if the infrared ones, if they're more energy efficient and cheaper to run than what that would be, I'd probably use that. So, perhaps the heated radiators to give the initial blast of warmth to the home, but then one of them to keep on throughout the day and just maintain that warmer level, rather than keep turning the heating on and off." (Week 1, day 1, am)*

They were not interested, however, in using infrared heaters instead of their current gas central heating system.

> *"Yes, they're good if you just want temporary heat, maybe, in a room for a little bit, not for proper heating, I don't think." (Week 1, day 4, am)*

Sustainability
Very few participants talked about how sustainability influences their decisions about heating systems. Those who did mention sustainability usually acknowledged that it is becoming increasingly important, but noted that other factors, especially cost, are more important.

> *"We'd both be intrigued to see how much it'd cost on a meter to have it on for a sufficient amount of time versus what you're paying at the moment for a normal gas rate heater. Granted, I know they want to get away from fossil fuels but… (Week 1, day 1, am)*

> *"The ranking system is the cost of installation plus running, and then the environmental implications of where the energy is coming from after that." (Week 1, day 3, pm)*

The move towards renewable energy was talked about as being something for the future, and not something that currently influences everyday choices.

> *"We said we can't just keep taking the fuel out of the earth because look what it's doing to global warming. So, there'll be no coal, no gas. We have to find an alternative." (Week 1, day 3, am)*

3.3.4 Approach to heating the home

This theme is about how participants' preferences and practices around heating their homes affect their willingness to consider infrared heating. There are four sub-themes: saving money; keeping warm; operating patterns; and conflict.

Saving money
This sub-theme is about how participants' heating patterns are shaped by wanting to save money. Sometimes this can be because people would prefer to keep costs as low as possible so they can spend money on other things. Sometimes it's because they are living alone and don't feel it's worth heating the whole house. Sometimes it is because people simply can't afford to heat their home to their preferred temperature.

> *"Me and my partner, we're quite conscious of the cost benefits of turning certain things on and off anyway just to try and save as much money as we can. Granted, we're not bad financially. In fact, we're normally quite good but I'd rather save money and turn things off that need turning off, rather than just simply wasting money away." (Week 1, day 1, am)*

> *"I don't really use central heating. Normally, because I'm on my own, it's just one room per time." (Week 2, day 2, am)*

Participants talked about the strategies they used to keep warm without increasing their heating bills, including wearing lots of layers, using a heated throw, using a portable heater, drinking hot drinks, and leaving the house to go to heated public places.

> *"I can cope without having the heating on because I'm conscious of the money side of things now so I'm just managing. I've got a Rocky Balboa kind of dressing gown. I just throw that on, or I'll just make a cup of tea or something like that." (Week 1 day 1, pm)*

"I've got one of those vortex heaters, like fan heaters, also cooling. Literally, you turn one of them on and you set the temperature and within five minutes, and I think it's 15 pence an hour it's working out at. So it's a lot more financially beneficial to have one of them." (Week 2, day 2, am)

Keeping warm
In contrast, some participants talked about their practices being based on the need to feel warm in their homes. For some, it is a personal preference, while others talked about needing to keep their home warm because they have children, or they have a health condition that means it is important for them to keep warm. Some talked about wanting a warm house for specific periods, such as when they have visitors.

"I never turn it off. Plus, I have to have windows open. The only different thing is it goes on a cooler setting between 10 o'clock in the evening and 4 o'clock in the morning. I have to have it on 24-7]. I can't be cold whatsoever. I have to be comfortable." (Week 2, day 3, pm)

"I have four children at home so I need to keep my house warm." (Week 3, day 3, am)

"Yes, with my knees and stuff like that. Because sometimes my body just seizes up so it costs me a fortune. You don't get extra money for being poorly, not for heating anyway." (Week 3, day 1, am)

Some participants keep their heating on all the time without regard for the cost, while others keep an eye on their smart meter, but it's more important to keep warm than to save money.

Operating patterns
This sub-theme is about how participants time their heating to come on and turn off, and the temperature they heat their home to. Most participants used a thermostat to control the temperature of their home, with their heating programmed to turn on in the morning for a few hours, and then again in the evening for a few hours until they go to bed. Some keep their heating on during the day, although often at a lower temperature than the morning and evening.

There was a lot of variation in their thermostat setting, from 15 degrees to 23 degrees. However, some participants did not know what their thermostat was set to.

"I have mine around about the 21, 22 mark. If my kids are around I normally crank it to 23 for an hour and put it back down to 22 to maintain that heat. I'd say 22 is a good number usually." (Week 1 day 1, pm)

"When the kids are there, then I'll have the heating on probably about 20, 21. If I'm on my own with the dog, I won't have it on." (Week 1 day 4, pm)

Some participants used additional heaters, which included underfloor heating in specific rooms, electric fires, and portable heaters. Those who had underfloor heating talked about how it warms the room to a comfortable temperature without it ever feeling too hot or too cold.

“Well, at daytime, I have my gas on and at night time, I put my electric fire on. So I’ll shut the door because I’d be in just the front room at night watching a film before I go to bed. So I’ll switch my gas off for the central heating of the house and I’ll just have my electric fire on, and it’s a fan and I can switch it off and on as and when to save electric.” (Week 1, day 2, pm)

Many participants use a smart thermostat, such as Nest or Hive. They used this to avoid using the heating when nobody is home and they all appreciated the flexibility that this provides. Others simply used their thermostat as a way of turning their heating on and off: turning it up to the highest setting when they want their heating to come on, and down very low when they want their heating to turn off.

“It can be freezing, I’ll whack it up. And then it’s, turn the thermostat down, turn the thermostat up.” (Week 3, day 1, am)

Several participants didn’t know how to use their thermostat or control their boiler, or talked about how others in their family didn’t know.

“I do mine manual. I cannot do those timer things. I just can’t.” (Week 1, day 1, am)

“I’ve not set the temperature, my boyfriend’s done it, so I just turn the boiler on when I’m cold.” (Week 1, day 2, pm)

Conflict

Several of the participants highlighted that people living in the same home can have different temperature preferences. They talked about how this is normally handled with good-natured pseudo-exasperation, with one family member complaining about the heat, or the cost of the heating, or conversely, about having to tolerate a colder temperature than they would like. Occasionally, however, participants talked about genuine resentment, or “thermostat wars” in which different household members turn the heating up or down while hoping other family members don’t notice.

“Well if I’m in the house it’s not on. If she’s in the house it’d be at 22.” (Week 1, day 1, pm)

“My wife likes to live in a sauna!” (Week 3, day 3, am)

“I'm in a student house but we don’t often have the heating on. My housemates they won't let us have it on, so I'm used to being cold.” (Week 2 day 3, am)

A few talked about how the infrared heaters could offer a solution to this, with the people who preferred warmer temperatures sitting closer to directly in front of the heaters while those who preferred it cooler sitting further away or to the side.

3.3.5 Focus group key findings and implications for future research

- Ceiling-mounted and wall-mounted heaters give different thermal experiences.
- Wall heater height could be investigated so that they heat more of the body while seated.
- Heaters are often viewed as pre-primary (overcome long response times with existing heating sources) or, secondary heating sources or single-room-only heating.
- To test participant assumptions on the situations in which it may be suitable to consider:
    - Newer and older homes
    - Smaller and larger rooms
    - Different exposure of occupants to panel, i.e., regularly and irregularly shaped rooms different panels obstructions (furniture etc.)
    - A measure of insulation and airtightness
- To explore whether ceiling panels can heat the depth of the room sufficiently, homes with children should be included.
  Participants found it difficult to rate comfort, any field trial should use introduce a qualitative assessment methods (e.g., ISO10551 [20][v]).

[v] This international standard presents a range of questions to evaluate the thermal environment, with responses presented on a simple Likert scale. Specific questions ask the respondent to rate their thermal state (cold/comfortable/hot), thermal preference (colder/no change/warmer), and personal judgement (acceptable/unacceptable, tolerable/intolerable). Using this standard approach allows the researcher to separate thermal sensation from subjective preference, providing a more nuanced appraisal of both thermal comfort and the overall thermal environment.to counter this and should include a qualitative component.

4 Recommendations for any future IR field trial

The results from the literature review and user experience tests cannot be used to determine if a large-scale field trial would be needed. However, they can identify the lack of existing data for the in-use application of IR heating systems and inform recommendations for any future large-scale field trial to investigate the effectiveness of IR heating in homes. This chapter outlines these recommendations and how this impacts the experimental design and sample (including subgroups) needed for a field trial. It should be noted that at this time DESNZ does not have plans to deliver an IR field trial.

4.1 Types of homes

Table 4-1 summarises the priorities for which homes should be selected for a trial. Shown are high-priority issues emerging from the research.

Table 4-1 Considerations on the types of homes to include in a field trial

Variable	Requirement/subgroups	Consideration
1. Room shape & shielding	a: No obstacles/shielding b: Obstacles/shielding	**High priority**: The biggest influences on comfort was the ability to maintain a direct line of sight with IR panels. The impact of rooms with unusual shapes or other obstacles should be analysed.
2. No planned alterations	a: No other retrofits planned that can affect the line of sight or comfort	**High priority**: No homes should be included if they are anticipating any changes to their fabric or heating system as this will compromise analysis.
3. Room size	a: small rooms (e.g., $<10m^2$) b: large rooms (e.g., $>10m^2$) c: high ceiling rooms (e.g., $>2.4m^2$)	**Medium priority**: Distance away from IR emitters was found to impact comfort, additionally users are concerned there may be inadequate wall space in most rooms for optimal positioning.
4. Fabric energy efficiency	a: High (e.g., 2010 Regs) b: Medium (e.g., insulated cavity wall) c: Low (e.g., uninsulated solid wall)	**Medium priority**: The energy efficiency of the home will affect the perceived comfort delivered by IR (e.g., wall surface temperatures).
5. Air permeability	a: <8 m^3/m^2/hr@50pa (2022 Regs) b: 8-15 m^3/m^2/hr@50pa c: >15 m^3/m^2/hr@50pa	**Medium priority**: The presence of draughts may undermine comfort delivered by IR, affecting the reliability of results but providing relevant data.
6. House type	a: Flats / mid terrace b: End terrace / Semi-detached c: Detached	**Low priority**: It may not be essential to compare all three groups since most stated impacts are related to internal conditions in the homes.

7. Exposed thermal mass	a: Covered floors b: Uncovered floors	**Low priority**: There was little data to describe the impact of exposed mass on IR (e.g., acting as a heat sink).

The room shape and size are highlighted as the most important issues since these affect the ability of occupants to directly experience the IR emitters (i.e., line of sight is maintained). Homes may have different room shapes, sizes, and layouts, meaning they have multiple variables listed below. While this may reduce the sample size of homes recruited, it adds complexity in terms of relating feedback from occupants to specific room variables, rather than the occupant experience in their home in general.

Fabric and ventilation heat loss are listed as medium priorities since cold wall surfaces and draughts are known to affect comfort and may pose challenges for radiant heating systems, but little data was collected in the user trials to understand the effect of this on comfort. Several groups are considered which adds complexity to the sample, it is likely that the air permeability will not be known until the home is recruited and so this may be a challenge to achieve a regular sample across this variable.

The fabric heat losses should be relatively simpler to identify based on generic building characteristics. Having three groups would indicate the range in performance across UK homes. However, if comfort is assessed to be achieved in homes with low thermal efficiency it may not be necessary to investigate homes with high thermal performance.

Since most of the variables are focussed on the internal environment house type may not need to be a major consideration but should be noted. Similarly, there is little evidence on the impact of the amount of exposed thermal mass on comfort for IR heated rooms, though this may be noted in the field trials.

4.2 Types of households

As important as the homes themselves are the occupants and Table 4-2 outlines the findings from the research. How people heat their homes is key and the groups identified in variables 1, 2, and 3 below are likely to experience differences in benefits from IR.

It may also be interesting to investigate how children respond to IR heating since this is currently an unknown though there are likely to be various household types in any sample of homes and this can be noted as a variable for consideration.

Since the types of householder could be important in determining the effectiveness of the IR heaters it will be necessary to include a filtering stage to the recruitment to ensure that a useful stratified sample is achieved.

Table 4-2 Considerations on the types of household to include in a field trial

Variable	Requirement / subgroups	Consideration
1. Occupancy patterns	a: Intermittent occupation b: Stay at home	**High priority**: Benefits of IR have been reported to be fast heat up times (though these were not able to be confirmed in the user trials), which indicates intermittency of occupation may determine the impact of IR.
2. Time and motion study in homes	a: Monitor the way occupants use homes, potentially to include a larger scale survey, outside of field trial (e.g., part of EFUS 3)	**High priority**: Determine how often occupants are sedentary (optimal conditions for IR) vs. moving around and not in the line of sight of IR emitters. This will inform the potential for IR to achieve savings
3. Space heating set points	a: <18°C b: 18°C to 21°C c: >21°C	**High priority**: Comfort is subjective and the set point to which homes are heated, will influence changes in comfort and fuel costs from switching to IR.
4. Proportion of home heated	a: Heat the whole home b: Heat part of home	**High priority:** Moving out of the proximity of IR heaters impacts comfort, so frequently moving between rooms could impact comfort.
5. Household type	Group 1: Families with children and vulnerable adults Group 2: Other households	**Low priority**: There has been no research to understand how IR is perceived by children and vulnerable adults and if panel mounting positions are appropriate.

4.3 Types of IR heaters

User experience trials confirmed the location of the emitter was significant in how participants reported their comfort and Table 4-3 summarises which variables should be prioritised for investigation in a field trial.

The literature and much of the feedback from the user experience trials outlined the benefits IR heating can provide in delivering top-up heat, especially where the incumbent heating system is a slow response system with lag times, or to temporarily heat limited spaces. However, the energy saving mechanism being investigated in this project is to replace existing whole house central heating systems, so these side benefits of IR should not be considered. Although there are a range of different manufacturers and products and controls, often these share identical or similar features. Additionally, the type of heat was not found to materially affect the comfort occupants experienced in the user trials, so the choice of IR heaters is less important as the benefits found in one technology are likely to relate to others. Indeed, it is likely that all radiant heating systems will share similar features, and this may be investigated via a sub sample.

Table 4-3 Considerations on the types of heating systems to include in a field trial

Variable	Requirement / subgroups	Consideration
1. Primary central heating	a: 100% IR central heating	**High priority**: IR can be combined with heat pumps or deliver top-up heating to aid comfort. However, the field trail must have 100 % IR central heating.
2. Technology	a: Type E b: Type F c: Other	**Medium priority:** The comfort voting did not identify significant differences in comfort between any heater types (IR or gas) except that coving heating was less comfortable than wall and ceiling mounted heaters. The focus groups did not identify any preference for panel types. This may be investigating via a sub sample but and difference may be expected to be small and difficult to identify.
3. Emitter location	a: Ceiling b: Wall c: Other	**Medium priority**: Heater mounted position was not found to significantly affect comfort, however, obstruction of emitters by furniture or other features obstructing the line of sight to emitters was significant which will be affected by mounting position. Emitter location also affect proximity to an emitter where room size is large. Other locations that have not been explored in this research (e.g., skirting) may need investigating via a sub sample.
4. Controller	a: On / off b: Modulating	**Low priority:** The user experience tests found no difference in comfort between IR, this may not need more investigation via a sub sample.

4.4 Types of data collection

Several sources of data should be collected as part of any field trial as outlined in Table 4-4. There is a range of data that could be collected; however, some data may be more useful to collect than others, which may help set the specification for the minimum expectations for data collection.

Table 4-4 Considerations on the types of household to include in a field trial

Variable	Requirement	Consideration
1. Comfort perception	Qualitative: Interviews / focus groups / diaries / open ended surveys	**High priority**: The trials found that qualitative feedback from participants yielded high quality data. It also identified that the use of quantitative voter preference data would not likely be useful or practical to deploy across a field trial since it required a high level of participant interaction. Comfort data are challenging to interpret, and it would be useful to consider using ISO 10551 [20].
2. Weather corrected energy use	Quantitative; fuel consumption pre- and post-IR installation including sub-metering for panels	**High priority**: While there are several determinants of the amount of fuel households use a comparison across the entire cohort of fuel consumption before and after the IR heaters are installed will indicate their success. A relatively large sample size (e.g., several hundred) for each distinct subgroup in the sample groups (e.g., emitter location or degree of shading), will be needed to detect a change. Pre-installation heating fuel consumption data should be a minimum of meter readings before installation and at the point of IR installation, or actual gas consumption data, plus local external air temperature at the homes, so that at a minimum degree day analysis can be performed.
3. Air and operative temperature	Quantitative; centre room air and black globe temperature sensors	**High priority:** to determine if homes are being heated to lower background air temperatures, while still maintaining comfort during IR heating the before and after air and operative temperatures in homes will need to be recorded. Sensor location will be important to ensure consistent readings throughout the trial.
4. Cost analysis	Quantitative: installation costs and running costs	**High Priority:** One of the main benefits of the IR heating systems is they are reported to have lower installation costs, however, less is known about the running costs which in this trial could be derived from the sub-metering of the panels post-installation, the pre-installation running costs could be derived from gas consumption pre-IR installation.
5. Building characteristics	Quantitative: Building survey	**High priority:** air tightness tests will be needed along with a general survey to give context to inform the interpretation of data (e.g., floor covering, ventilation, wall type, insulation, etc.).

Variable	Requirement	Consideration
6. Occupant survey	Quantitative: Pre and post-IR installation survey	**High priority:** while it will not be possible to extract qualitative data from all homes, it will be useful to deploy a before and after occupancy survey to extract data from households on their perceptions of transitioning to an IR system from their previous heating.
7. Surface condensation risk analysis	Quantitative; Room corner shaded air temperature sensors and RH sensors	**High priority:** Reducing air temperatures (by installing IR) in homes will increase RH and the surface temperature of walls. This has the potential to increase surface condensation risks in homes. Corners and junctions and areas shaded from heat emitters should be targeted with sensors pre- and post the IR installation.
8. Emitter surface temperature	Quantitative: Sensor on the emitter surface	**Medium priority:** One concern with emitters was found to be safety around surface temperatures and the potential for burns. Measuring this will also provide data on use frequency.
9. Comfort voting	Quantitative: time stamped voting preferences	**Low priority:** the user experience field trials showed that the use of comfort voting preferences was challenging to interpret and yielded intermittent data. It is possible a sub-sample could be asked to provide comfort voting as part of this trial to explore the methodology further, however, it is possible this will not produce useful data.
10. Validating comfort models	Quantitative: Modelling comfort	**Low priority:** Since most thermal comfort assessments use modelling and these models are validated against laboratory experiments rather than large field trials, this research could be an opportunity to validate existing thermal comfort prediction methods by undertaking modelling of the IR systems installed in a subsample of homes.

5 Conclusion

The three approaches to data collection have identified multiple findings to describe the potential for IR heating to achieve energy savings in homes. Some findings confirmed previous understanding (e.g., line of sight of IR is an important factor in achieving comfort) however some findings resulted in apparent contradictions (e.g., analysis from the focus group found there were differences in comfort preferences between gas and IR heating systems, and between IR technologies, while comfort voting data could not corroborate this). This highlights the variability in comfort between individuals, and the complexity around establishing reliable data on which to measure thermal comfort, which has implications for any future large-scale field trial.

Literature reviews
A systematic literature review was conducted to explore user experiences of infrared heating systems in domestic contexts. An additional review of grey literature was also undertaken which found further valuable information to understand infrared heating in domestic settings. The literature cites several benefits of IR, including energy savings (via reduced air temperatures) and low installation and maintenance costs. However, findings were often based on manufacture claims, modelled predictions, and for specific conditions that may not be representative of heating in homes. Additionally, fuel consumption savings were reported often related to multiple fabric and service improvements or did not provide evidence to support claims. This made it challenging to identify the specific benefits related to the IR heating system. Real world trials were rare, the most notable example was from a UK housing association, which identified serious concerns around user experience in homes, resulting in hundreds of IR systems being prematurely removed from homes. There is an insufficient amount of reliable published data on the use of IR heating systems in real-world contexts to effectively evaluate their potential as a low-carbon technology in the UK.

User experience trials
Feedback was sought from 114 participants who experienced different IR heating technologies and conditions via a test home located in an environmental chamber. The results suggest that IR heating can provide comfort to occupants, regardless of the type of IR heater installed. Feedback from the field trials suggested participants experienced comfort differently between ceiling mounted and wall mounted IR heaters, however, there was no measurable difference observed in the comfort voting. The participants stated that comfort was impacted by proximity to the IR heater and specifically the comfort voting identified that remaining line of sight with the heaters was essential to achieving comfort. Comfort was not, however, perceived to be consistently provided by the IR heaters, with occupants reporting that some areas of the room, and their body, were at times either overheated or underheated, which adversely affected their comfort. It was not possible to determine the time to comfort or discomfort since the occupants tended to report comfort at the start of the experiment and the rooms remained comfortable even when heaters were turned off before the end of the trial. Users mostly considered IR heating had the potential to be used as a top up or secondary heating rather than a replacement to their central heating.

Implications for future research

From these results, it is recommended that any future trial should investigate comfort where IR systems are obstructed or able to provide partial vs. total room coverage (i.e., maintaining line of sight of occupants) as a priority. Trying to compare different house and householder types as well as different types of IR heaters could create multiple subgroups in trials which will increase sample sizes significantly. Qualitative data is likely to be most useful in explaining experiences of IR heating and why it was successful in some situations or not in others. Quantitative data on the indoor and environmental conditions and the energy use in the home pre- and post-IR installation could provide an empirical evaluation of the change in weather-corrected fuel bills in homes post-IR installation and may reveal if behaviour change (reducing set point temperatures) did take place. Contextual information would be needed to explore other issues linked to IR including potentially lower installation costs and the potential for unintended consequences (e.g., increased surface condensation risk).

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7 Appendix, Systematic literature review

7.1 Scopus

Search terms were organised from the highest (Step 1) to lowest (Step 5) priority (Table 7-1). It is not uncommon for certain searches to have various spellings and forms of words. For instance, “Infrared” or “Infra-red” or even just “IR," are all variations that refer to infrared.

After a search was performed using step 3, i.e., ("Infrared" OR "Infra-red " OR "IR") AND ("heating") AND ("home" OR "house" OR "dwelling" OR "domestic"), 99 papers were returned when filtered by title/abstract/keywords. 54 of these articles appeared to be related to the Energy, Engineering, and Environmental disciplines; consequently, they became our focus while leaving out topics such as Chemical Engineering, Physics & Astronomy and Chemistry. If a search was performed using step 2, i.e., ("Infrared" OR "Infra-red " OR "IR") AND ("heating"), 267 papers were returned when filtered by title only. Similar to the previous search, 78 papers are from Energy, Engineering and Environmental subject areas.

The review process continued with a Title Filter, where the titles of papers were read and only those relevant to this context were kept. Filtering by title, abstracts, and keywords led to six appropriate papers while filtering by title alone uncovered just two.

Note that steps 4 and 5 were rejected as after the title/abstract/keywords filter, the results were less than satisfactory as compared to step 3. Step 4 was able to narrow down to 23 papers; however, after further title filtering, none of these was found relevant in this context. Lastly, step 5 resulted in just one paper being identified.

After a thorough title filter, seven papers were identified (Table 7-2). The abstracts of these papers were then read and evaluated to determine if they fit into the research context. Results showed that only one paper passed this filter out of the original seven; its reason is discussed in Table 7-2. This recent 2022 Energy and Buildings Journal article provided many relevant literature references and included a well-crafted literature review.

Table 7-1 Boolean search using Scopus

Step	Boolean	Search terms	Papers found, filtered by title/abstract/keywords	Papers found, filtered by title only
1	Start	"Infrared" OR "Infra-red " OR "IR"	336,940	58273
2	AND	"heating"	8,983	267
3	AND	"home" OR "house" OR "dwelling" OR "domestic"	99	0
4	AND	"test" OR "trial"	23	0
5	AND	“thermal comfort” OR "comfort"	1	0

Table 7-2 Selected papers after title filter using Scopus

Paper	Title	Title/ abstract/ keyword filter	Title only filter	Notes
1	Cost-effective occupation dependant infrared zonal heating system for operational university buildings	Y	Y	Relevant. Fair infrared heating installation on a university lecture theatre
2	An innovative approach towards enhancing energy conservation in buildings via public engagement using DIY infrared thermography surveys	Y		Irrelevant. Use of infrared cameras to evaluate the performance of houses.
3	Fabrication of low emissivity paint for thermal/NIR radiation insulation for domestic applications	Y		Irrelevant. This paper investigates how effective low emissivity paint can be used as a coating for radiation control, IR heating panels
4	Practical experience with IR-controlled supply terminals in dwellings and offices	Y		Irrelevant. IR in this paper means Infrared Spectroscopy, not Infrared heating panels

Paper	Title	Title/ abstract/ keyword filter	Title only filter	Notes
5	Assessing the airtightness performance of container houses in relation to its effect on energy efficiency	Y		Irrelevant. This paper uses Infrared Thermography to assess the airtightness of a building
6	The influence of thermal and solar radiation on the energy consumption of buildings	Y		Irrelevant. This paper applies weather-resistant infrared mirror coating to the building envelope.
7	Energy efficiency of electrical infrared heating elements		Y	Irrelevant. This paper characterises the radiant energy efficiency of infrared heating elements, but it is not in the domestic context.

7.2 Google Scholar

Utilising Google Scholar, it is possible to search for research papers, industry reports, and master's/Ph.D. thesis beyond just those in Scopus (Elsevier publisher).

Similar to Scopus's "AND," "OR," and "NOT" functionalities, Google Scholar has an advanced search function that provides detailed search results. The Advanced Search tool has three search bars, including "All of these words," "Exact phrase" and "At least one of these words" fields. The last entry field is a special "OR" function that allows for more flexible searching, while the first two are standard "AND" functions which require all keywords to be present in each result returned. Compared to Scopus, Google Scholar Advanced Search offers title and text-only searches and does not offer the same complex filtering options such as title/abstract/keyword search.

The Google Scholar search found that the full-text filter produced too many results (**Table 7-3**). Even after step 4, there were 5140 outcomes. Upon scanning the initial 100 entries, only two of them proved to be useful. When using a title filter instead, however, it yielded only four papers in total after step 3 - three of which drove relevant research. If step 2 is used for filtering by titles instead, it resulted in 2450 results; yet again upon examining the first hundred entries, just one applied to our purpose. Therefore, an extra step (Step E) was performed which involved combining the Step 1 and Step 2 search term “infrared heating”, with the Step 3 search term “thermal comfort”.

This search method filtered by full text resulted in over 325 articles - though careful filtering of titles was necessary as many were irrelevant, such as those related to food processing and drying. After title filtering, ten of them are relevant. After abstract filtering, it was revealed that Google Scholar yielded results that pertained not just to domestic applications but also other practical uses of infrared heaters with regards to thermal comfort evaluation, including applications for industrial buildings [21], university buildings [22], vehicles [23, 24] and trains [25].

Although these papers can provide a valuable starting point for this project, they may not be adequate when it comes to developing the methodology and comparing results (**Table 7-4**).

Additionally, Google Scholar yielded a variety of theses and industry reports in Dutch [11, 13], which are relevant to this research context. Corsten 2021 developed models to evaluate the overall performance (energy and thermal comfort) of infrared panels compared with conventional heating solutions for Dutch residential buildings [11].

According to Corsten's 2021 reference list, Biliotti's 2020 and Knijff's 2018 can be found [14, 15] (**Table 7-5**). Biliotti 2020 uses dynamic simulation models to compare the efficiency of infrared heaters and heat pumps, while Knijff 2018, an industry report, takes an empirical approach by comparing the cost of installing IR heaters and heat pumps in Dutch dwellings. Perhaps one of the most beneficial studies is Van Loy et al. 2021, in which infrared heating panels are put to the test with human occupants, and thermal comfort metrics are measured as an outcome [12].

Table 7-3 Boolean search using Google Scholar

Step	Filter	Search terms	Papers found, filtered by full-text	Papers found, filtered by title
1	With at least one of the words	"Infrared" OR "Infra-red " OR "IR"	5,890,000	798,000
2	With all the words	Heating	5,280,000	2450
3	With the exact phrase	Thermal comfort	32900	4
4	With all the words	Home house dwelling domestic	5140	0
E	With all the words	“Infrared heating” AND “thermal comfort”	324	0

Table 7-4 Selected papers after title filter using Google Scholar

Paper	Title	Title/ abstract/ keywords filter	Title only filter	Abstract filter
1	Infrared heating as an adjunct to achieve vehicle occupant thermal comfort	Y	Y	Irrelevant. The assessment of infrared heaters is conducted on motor vehicles, not in a residential setting.
2	Studies on Infrared Radiation Heating for Increasing Thermal Comfort	Y	Y	Irrelevant. This paper mainly provides theoretical information on infrared heating and its effects on thermal comfort, although not in a domestic setting.
3	Evaluation of Infrared Heating as an Adjunct to Achieve Occupant Thermal Comfort in Cars	Y	Y	Irrelevant. The assessment of infrared heaters is conducted on motor vehicles, not in a residential setting.

Paper	Title	Title/ abstract/ keywords filter	Title only filter	Abstract filter
4	Cost-effective occupation dependant infrared zonal heating system for operational university buildings		Y	Relevant. Fair infrared heating installation on a university lecture theatre
5	A comparative performance assessment of infrared heating panels and conventional heating solutions in Dutch residential buildings		Y	Relevant. Through the use of dynamic simulation models, this report seeks to contrast and compare infrared heating panels with heat pumps in Dutch homes.
6	Effect of thermal comfort/discomfort due to infrared heaters installed at workplaces in industrial buildings		Y	Irrelevant. The evaluation of infrared heaters is done in an industrial context, not in a domestic context.
7	Effects of personal control for thermal comfort in long-distance trains		Y	Irrelevant. The evaluation of infrared heaters is done in trains, not in a domestic context
8	Analysis of the Potential of Decentralized Heating and Cooling Systems to Improve Thermal Comfort and Reduce Energy Consumption through an Adaptive Building Controller		Y	Irrelevant. This paper evaluates the effectiveness of Decentralised heating systems, such as office chairs with a built-in heating function and thermoelectric partitions. However, it does not include infrared heating systems in its assessment.
9	Personal heating in dwellings as an innovative, energy-sufficient heating practice: a case study research		Y	Relevant. Testing Infrared heating panels with human occupants is highly relevant to this project. This paper could stand out as the most useful resource to reference and inform progress.

Paper	Title	Title/ abstract/ keywords filter	Title only filter	Abstract filter
10	Comparative study on energy consumption of gas-fired infrared radiant and convection heating		Y	Irrelevant. This paper applies simulation models to measure the performance of industrial factory buildings instead of domestic contexts.

Table 7-5 Title and description of the related papers from the papers searched via Google Scholar

Paper	Title	Description
1	Case Study of the Differences between Infrared Heating and Gas Heating in Old Residential Buildings, Using Comparative Measurements.	Research has proven that infrared heating is a realistic alternative to common heating systems. Despite the potential savings, it is not given sufficient consideration in standards and regulations such as EnEV.
2	Performance assessment of heating solution for Dutch residential houses: evaluation of IR-Panels systems and comparison with heat pumps.	Evaluates the available methodologies to assess thermal comfort in residential environments equipped with infrared (IR) panels,
3	Praktijkvoorbeelden aardgasvrije woningen	Industry report in Dutch context comparing the use of IR heating panels and heat pumps

7.3 Grey literature

A summary of the grey literature reports reviewed is presented in **Table 7-6**.

Table 7-6 Summary of Grey literature

Reference	Description
[13]	Infrared heating was reported as a realistic alternative to common heating systems. Despite the potential savings, it is not given sufficient consideration in standards and regulations such as EnEV.
[16]	From 2017 to 2019, the IR-Bau research project addressed the question of whether infrared heating (direct electric heating) can be an alternative to heat pump systems in the sense of a low-tech solution in very well-insulated residential buildings from an economic and ecological perspective.
[26]	IR radiant heating systems provide benefits over standard convention (air) heating systems, with 10% and over 50% energy savings possible depending on the test and system.
[27]	Residential buildings in China use convective or radiant heating terminals, which have different effects on thermal comfort. This study compared the thermal comfort of different types of heating terminals which includes an objective field test and subjective artificial chamber experiments.
[28]	Radiant heating and cooling systems are more efficient than all-air systems, based on 8 conclusive studies. More evidence is needed to confirm this conclusion definitively.
[29]	This study evaluates the potential application of low-temperature radiant ceiling heating systems in buildings with a low space heating load.
[30]	This review analysed operational data of Ambion's Low Carbon Heat Panels utilising their CCIR technology. Results show that 91% of the households in the dataset had a higher performance ratio than standard electric convection heaters, and 45% of terraced houses and 67% of flats had a higher performance ratio than air source heat pumps.
[31]	This study performed tested infrared heating panels in 20 households. They are delighted with and enthusiastic about the new IR heating: 2 operated 24/7, 12 used time scheduling & others ad-hoc adjustments. Running costs did not emerge as a major concern but households lacked a good grasp of how electricity usage affected cost.
[32]	This study performs a small domestic heating trial with 12 volunteer households in rural Wales. The aim was to explore whether a person-centred, hybrid approach to domestic heating could offer a way to reduce energy consumption and improve people's thermal comfort.
[18]	Hebridean – This internal report by a social housing provider monitored 95 IR heating installations and operations and performed occupant evaluation surveys.
[17]	This literature study on low-temperature domestic radiant heating is not specific to IR heating systems but raises many of the issues discussed here with findings that are generally also applicable to IR systems.

7.4 IR Heater archetypes

7.4.1 Type A

Type A heaters work in the short-wave range of the infrared (IR) region of the electromagnetic spectrum (also known as near IR or NIR), ranging from 0.78 μm to 1.4 μm wavelengths. These heaters provide excellent penetration depth. The emitters are equipped with high-quality reflectors to direct the IR radiations to high concentration levels to achieve optimum reflection levels for the required application and increase efficiency. These emitters have considerably short response times and can reach their full power in a few seconds to less than a second. The elements typically glow during operation, though non-glowing models are also available. They can be manufactured in a wide range of shapes and dimensions.

Elements: Typical elements used in Type A heaters are tube emitters (e.g., quartz halogen tubes, quartz tungsten tubes, and quartz carbon fibre tubes).

Rated power & voltage: Their rated power ranges from 1 kW to as high as thousands of kW (Voltage: 220V to 420V).

Filament temperature: The filament temperature ranges from 1,800°C to 2,600°C.

Surface temperature: 500°C to 900°C

Application: Industrial applications (e.g., heating, and drying processes, thermal treatment of materials, etc.) in various industries, including furniture manufacture, cable, rubber and plastics industry, automotive industry, aerospace industry, solar wave manufacture, textile industry, print application, etc. Indoor and outdoor applications: portable/fixed heaters for indoor and outdoor use (home, conservatory, parking spaces, churches, village halls, workshops, etc.).

7.4.2 Type B

Type B heaters work from 1.6 μm to 2.0 μm wavelengths within the medium-wave range of the infrared (IR) spectrum (also known as mid-IR or MIR, ranging from 1.4 μm to 3.0 μm). Medium wave heaters quickly heat the surface and thin layers and have a very high absorption level by water layers. The emitters are equipped with high-quality reflectors to direct the IR radiations to high concentration levels to achieve optimum reflection levels for the required application and increase efficiency. Since medium-wave IR heaters transfer heat to the air, they can be categorised as both convective and infrared heaters. These emitters have short response times and can reach their full power between half a minute to four minutes. The elements typically glow during operation. The disadvantage for outdoor applications is that the convective aspect is lost to the outdoor environment. They can be manufactured in a range of shapes and dimensions.

Elements: Typical elements used in Type B IR heaters are tube emitters (e.g., quartz tungsten tubes and quartz carbon fibre tubes).

Rated power & voltage: 750 W and above (Voltage: 230V)

Filament temperature: 1,000°C to 1,500°C

Surface temperature: Up to 900°C

Application: Industrial applications include the drying process and processing of plastic foils and sheets). Commercial indoor and outdoor applications include heating workshops, warehouses, and restaurant courtyards.

7.4.3 Type C

Type C heaters work from 1.5 μm to 8.0 μm wavelengths covering both medium-wave IR or MIR (ranging from 1.4 μm to 3.0 μm) and long-wave IR (or far IR, FIR) (ranging from 3 μm to 1000 μm). These heaters are equipped with high-quality reflectors to direct the IR radiations. These emitters have short response times and can reach their full power between half a minute to five minutes. They can be wall or ceiling mounted. However, minimum clearance from the ceiling and wall, as prescribed by the manufacturer, should be maintained. Some products need to be installed at a prescribed minimum height and angle. They can heat different room sizes depending on the physical properties of the fabric (i.e., airtightness and insulation levels). Their design is compact. Similar to Type B heaters, the MIR heaters have a glare. However, the FIR heaters typically do not have any glare as they work at much lower temperatures. The disadvantage of MIR heaters for outdoor applications is that the convective aspect is lost to the outdoor environment. They can be controlled using different methods, including plug-in only, ON/OFF switches, thermostats, Wi-Fi/smart apps, remote control, and passive infrared (PIR).

Elements: Typical elements used in Type C heaters are tube emitters (e.g., quartz carbon fibre tubes and quartz tubes with resistance coils such as Fe-Cr-Al alloy).

Rated power & voltage: 50 W and above (Voltage: 230V)

Filament temperature: Maximum 300°C in FIR and 1000°C in MIR heaters

Surface temperature: Up to 120°C in FIR heaters. From 95°C to 750°C in MIR heaters.

Application: Industrial applications include locally targeted heating, drying painted objects, thermoforming, packaging, welding stations, preheating, etc. Domestic/commercial applications include patios, bars, restaurants, and café. Suitable for indoor/outdoor applications.

7.4.4 Type D

Type D heaters work from 2.0 μm to 10.0 μm wavelengths, covering both medium-wave IR (MIR, ranging from 1.4 μm to 3.0 μm) and long-wave IR (or far IR, FIR, ranging from 3 μm to 1000 μm). They are similar to Type C heaters in nearly all aspects. However, MIR and FIR heaters of this type do not have any glare. This makes them a suitable choice for locations where no glare is preferred (e.g., schools, colleges, offices, or a personal preference) or where light has an adverse effect (e.g., hospitals, animal enclosures, etc.).

These emitters have short response times and can reach their full power between half a minute to five minutes. They can be controlled using various methods, including plug-in only, ON/OFF switches, thermostats, Wi-Fi/smart apps, remote control, and passive infrared (PIR).

Elements: The elements used in Type D heaters are made from Ceramic.

Rated power & voltage: 150 W and above (Voltage: 230V)

Filament temperature: Maximum 300°C in FIR and 1000°C in MIR heaters

Surface temperature: Up to 120°C in FIR heaters. From 95°C to 750°C in MIR heaters.

Application: Industrial applications include thermoforming machines and ovens for drying and curing parts warming applications (e.g., to thermoform acrylic sheet for hot tub production, cure foam on speaker housings, preheat carbon fibre fabric, etc.). Domestic and commercial property applications include large indoor spaces such as warehouses and garages, hot yoga studios, large meeting rooms, restaurants, covered terraces, etc.

7.4.5 Type E

Type E heaters work from 3.0 μm to 15.0 μm wavelengths, covering the long-wave IR (or far IR, FIR) (ranging from 3 μm to 1000 μm). They are available in various shapes and finishes, including powder coated Aluminium, mirrored safety glass, and ESG Safety Glass with pictures. These IR heaters can be installed on the wall or the ceiling or used as portable IR heaters. For ceiling-mounted heaters, a clearance from the ceiling should be maintained. They do not have any glare and can be installed in all domestic indoor areas. They can heat different room sizes depending on the physical properties of the fabric (i.e., airtightness and insulation levels). Therefore, a combination of ceiling-mounted, wall-mounted, and portable heaters in a room might be necessary to accommodate indoor thermal comfort. These emitters have a response time of at least five minutes. They can be controlled using various methods, including plug-in only, ON/OFF switch, thermostats, Wi-Fi/smart app, remote control, and passive infrared (PIR). A combination of different control techniques is also possible (e.g., smart app plus PIR).

Elements: Typical elements used in Type E heaters are carbon crystal, carbon fibre, Aluminium, and Stainless steel, depending on the target FIR intensity.

Rated power & voltage: 200 W to 3000 W (Voltage: 230V)

Filament temperature: Maximum 300°C

Surface temperature: 60°C to 300°C

Application: Domestic indoor applications. Use in bathroom, kitchen, living area or use as a personalised portable heater.

7.4.6 Type F

Type F heaters, known as film heaters, work from 8.0 μm to 15.0 μm wavelengths, falling under the long-wave IR (or far IR, FIR) types of heaters (ranging from 3 μm to 1000 μm). These emitters have a response time of at least five minutes. These heaters can be embedded into the building fabric (wall, ceiling, and underfloor) or used as portable heaters. The embedded heaters have a response time of 15 to 45 minutes, depending on the room temperature. They can be controlled using various methods, including plug-in only, ON/OFF switch, thermostats, Wi-Fi/smart app, remote control, and passive infrared (PIR). A combination of different control techniques is also possible (e.g., smart app plus PIR).

Elements: Typical heating elements in Type F heaters are Graphite or Grafoil, Graphene, printed on a thin film.

Rated power & voltage: 8W/m2 to 400W/m2 for embedded types. Up to 450 W in portable types (Voltage: 220V to 240V).

Filament temperature: Maximum 90°C.

Surface temperature: 60 to 65 °C (exposed), 29°C to 31°C (embedded)

Application: Domestic and commercial indoor applications. Used to heat the entire building if embedded into the floor (as underfloor heating) and walls and ceiling. Also, they can be installed on the wall or used as personalised portable FIR heaters.

7.4.7 Conductive heaters

Conductive heaters, known as mat heaters, are designed to be embedded into the building fabric (walls and underfloor only). While Type G heaters are not categorised as IR heaters by the manufacturers, they work similarly to film heaters, so listed here. They can be controlled using various methods, including plug-in only, ON/OFF switch, thermostats, Wi-Fi/smart app, remote control, and passive infrared (PIR). A combination of different control techniques is also possible (e.g., smart app plus PIR).

Elements: Typical elements used in Type G heaters are made from Nickel, Iron, and Copper and covered with a protective mesh.

Rated power & voltage: 800 W/m² to 200 W/m² (Voltage: 230V)

Filament temperature: Maximum 200°C.

Surface temperature: 60 to 65 °C

Application: Domestic and commercial indoor applications. Used to heat the entire building if embedded into the floor (as underfloor heating) or walls.

7.4.8 Control systems:

Different manufacturers offer various methods to control their IR heaters.

Plug-in (with/without the on/off switch on the heater)

This control method only allows plug-in of the heater to a power supply and switch ON/OFF if a switch is provided. The user needs to unplug the heater or switch it off to stop it from operating. This way, the heater works at its rated power as long as it is plugged in/switched ON.

The thermostat control (mains-powered, battery-powered, portable plug-in)

These thermostats have different designs for their power supply, including mains-powered (hard wired), battery-powered, or portable plug-in. These systems enable operating IR heaters in various ways, including a manual temperature mode, a 7×1 day program mode, and a holiday (or Away) mode. Some models are Wi-Fi enabled and can be accessed via a Smart app with Alexa & Google Home voice control. These systems will turn IR heaters on if the room temperature is below the desired temperature and turn them off once the desired temperature is reached or exceeded. In some models, it is also possible to set the surface temperature of the heater(s). Some heaters are equipped with remote control, as well. Some types can be paired to more than one heater meaning multiple heaters within a room can be controlled with the same thermostat. Some models can detect an open window(s). They stop working as soon as a sudden indoor temperature drop of 1.5°C to 2.0°C is detected within a short period (e.g., less than three minutes). In some designs, a PIR sensor can be integrated into the WiFi-enabled thermostats to deactivate the IR heaters or set the room temperature at a lower set point while the room is unoccupied. One sensor for each room is required to check for occupancy in every room.

Existing thermostats switch the heaters OFF after the room/panel surface temperature reaches the desired setpoint, which causes discontinuation of the IR radiations for up to twenty minutes. A new generation of controls is being developed where instead of existing ON/OFF cycles (heaters are either working at their capacity or not working), they modulate IR heaters by frequently switching them ON/OFF in a quasi-continuous mode (i.e., the time interval that a heater stops radiating decreases to seconds or milliseconds). According to the manufacturers, this new control method could promote the comfort level of occupants by providing quasi-continuous radiation while maintaining the room/panel surface temperature at the desired setpoint.

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