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Increasing Thermal Comfort: How Colour and Fabric Composition of Clothing Impacts Warmth

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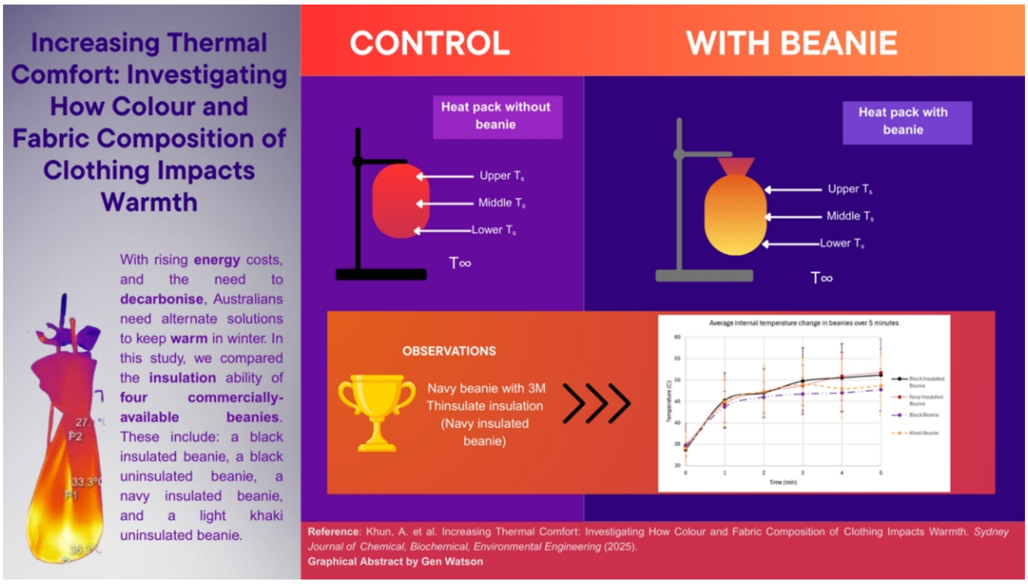
Abstract

As energy costs rise and carbon reduction targets intensify, passive strategies to improve thermal comfort indoors are increasingly important. This study evaluates the heat retention performance of four commercially available beanies differing in colour, composition, and insulation type to determine which materials most effectively limit heat loss. Using a silicone heat pack as a controlled thermal source, internal and surface temperatures were measured over time to quantify thermal conductivity and infer insulation capacity. Results showed that insulated beanies, particularly the navy beanie, retained greater heat over five minutes compared to uninsulated alternatives. Although darker colours are expected to absorb and retain more heat, the navy insulated beanie conserved more heat than the black insulated beanie, indicating that colour has minimal impact under typical indoor conditions. Thermal conductivity (k) values were calculated but are only partially representative due to complex multilayered structures, air gaps, and mixed heat transfer modes. The findings suggest that material layering and structure, rather than colour or fabric composition alone, play dominant roles in thermal retention. These insights support the potential for targeted clothing choices to enhance personal warmth in low-energy domestic settings.



Keywords: insulation, thermal comfort, thermal conductivity, clothing materials, heat retention

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1 Introduction

Many Australian homes offer limited protection from the cold, lacking the insulation and heating systems common in colder climates. This results in significant indoor heat loss during winter, often compensated for with electric heating; an increasingly expensive and carbon-intensive solution. As electricity prices rise and national decarbonisation efforts intensify, there is a growing need for low-energy strategies that maintain indoor comfort without increasing emissions[1, 2].

Clothing presents a simple yet underexplored solution [3]. By modulating heat exchange between the human body and its environment, clothing can significantly influence thermal comfort. This study investigates the thermal performance of everyday fabrics in a domestic context, with the aim of informing energy-efficient clothing choices[4]. We hypothesise that: The black insulated beanie will exhibit the highest heat conservation. Furthermore, beanies with a higher proportion of synthetic fibers (e.g., polyester) will retain more heat. These hypotheses are grounded in established heat transfer principles. Thermal conductivity (k) governs the rate of heat flow through fabric fibres, while the convective heat transfer coefficient (h) affects energy exchange at the fabric-air interface[5]. Materials such as wool and synthetics with embedded air pockets exhibit low k values, acting as thermal resistors. Multi-layered or thick fabrics further suppress convective currents, enhancing insulation. Additionally, fabric colour influences radiative heat transfer - darker colours, with higher emissivity and absorptivity, typically absorb and emit more thermal radiation than lighter-coloured ones[5].

Despite the extensive literature on fabric insulation in outdoor and extreme environments, there is limited research on the thermal performance of common garments in domestic settings[6]. This study aims to address that gap by evaluating the heat retention of four commercially available beanies differing in fabric type, colour, and insulation: a black insulated beanie, a black uninsulated beanie, a navy insulated beanie, and a khaki uninsulated beanie.

Using a controlled thermal source to simulate skin temperature, we measured the internal and surface temperatures of each beanie over a five-minute period. The results aim to inform practical, low-energy strategies for maintaining warmth indoors through clothing selection.

2. Method

2.1 Experimental Methodology

To begin the experiment, multiple silicone heat packs were placed in an oven and heated for approximately 20 minutes. After this period, the average surface temperature of the heat packs was found to be around 45°C, based on thermal camera readings taken during a control test. While the heat packs were warming, the experimental setup was assembled. A retort stand and clamp were used to hold the thermal camera in place, ensuring a consistent and stable view of the test area. A second retort stand, positioned opposite to the camera, was used to suspend each beanie during testing. The complete setup, including both stands and the camera-beanie arrangement, is shown in Fig. 1.

Once the heat packs were ready, an initial control test was conducted using a heat pack on its own. This control was placed within the view of the thermal camera, and surface temperatures were measured using the P2 Pro thermal camera app. Four surface measurements were taken every minute: the upper, middle, and lower regions of the heat pack, as well as the ambient room temperature.

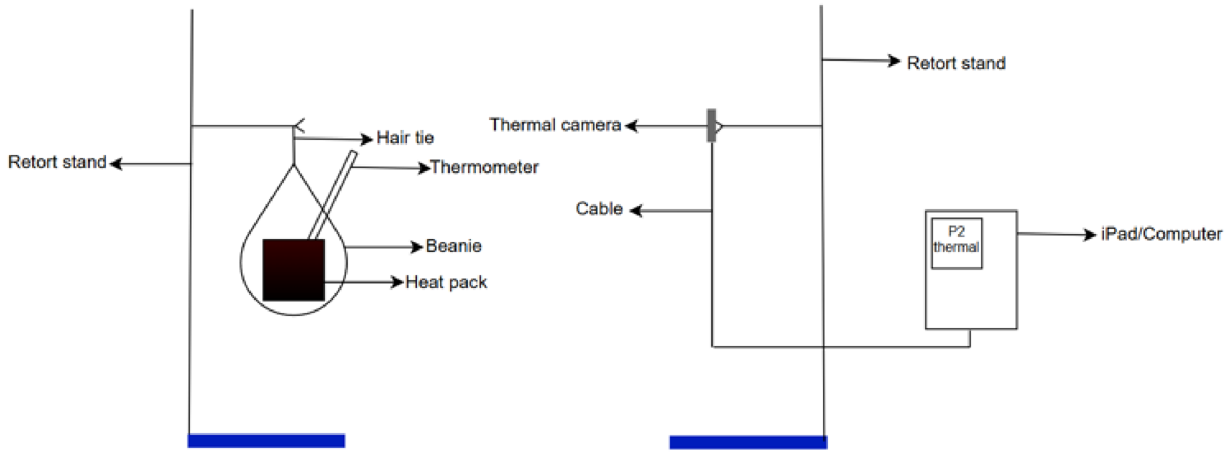

Figure 1: Diagram of experimental setup.

Next, testing began on the beanies. A freshly heated pack was inserted into the first beanie and secured with a hair tie. The beanie was clamped on the stand facing the thermal camera. A thermometer was inserted through the beanie fabric to measure internal temperature. Because the beanie was not see-through, the thermometer's exact position couldn't be checked, but care was taken to make sure it touched the heat pack each time. The same insertion method was used for all beanies to keep things consistent. Surface and internal temperatures were recorded every minute using the thermal camera and a thermometer, respectively. While measurements were taken as close to each minute as possible, slight human timing errors may have occurred.

This procedure was repeated for all four beanies: a khaki non-insulated beanie, a black non-insulated beanie, a black insulated beanie, and a navy insulated beanie. The entire experiment was performed four times, with three replicates for each beanie to ensure accuracy and repeatability.

2.2 Calculation Methodology

To analyse the results, heat loss from the pack was calculated using the formula:

$$Q = mc\Delta T \qquad (1)$$

Where m is the mass of the pack in kilograms (kg), c is its specific heat capacity in Joules per kilogram per Kelvin ($J.Kg^{-1}.K^{-1}$) , and T is the change in internal temperature over 5 minutes in Kelvin (K). This gave heat loss in Joules (J), which was then divided by 300 seconds to give power in Watts (W).

Surface area was estimated assuming the beanie-heat pack setup was roughly spherical:

$$A = 4\pi\left(r_{heatpack} + r_{beanie_{thickness}}\right)^2 \qquad (2)$$

Where A is the surface area in square meters(m^2), $r_{heatpack}$ is the radius of the heat pack in meters(m), and $r_{beanie\ thickness}$ is the radius of the beanie in meters.

Using these values, the thermal conductivity k of each beanie was calculated as:

$$k = \frac{Q \times L}{A \times (T_2 - T_1)} \qquad (3)$$

Where k is the thermal conductivity in Watts per meter kelvin ($W.m^{-1}.k^{-1}$), L is the thickness of the beanie in meters (m), T_1 is the internal temperature in Kelvin (K), and T_2 is the surface temperature in Kelvin (K).

It is assumed there is perfect thermal contact between the heat pack and the beanie throughout the experiment. For calculation purposes, the thermal camera readings are considered 100% accurate. The combined beanie and heat pack are collectively referred to as the "system" in this study.

3. Results

The objective of this report is to determine which beanie insulates heat best. This will be determined by the beanie that yields the best conduction value (a smaller k-value indicates better efficacy for use). The different colours, composition and presence of an insulating layer were the most significant factors.

3.1 Assumptions

This reaction was assumed to be in steady state such that the rate of convection and conduction occurred at equal magnitudes. Three repetitions of the experiment were performed and an average value was taken for the calculations. The thermal camera measured temperature at points labelled "P1", "P2" and "P3" as per Fig. 2. However, the average temperature for the surface temperature was the average between P2 and P3 since P1 was an inconsistent measurement. The density of the heat pack for silicone beads was assumed to be 1100kg / m3 and the heat capacity of silicone beads was assumed to be 1250 J/kg K[8] The mass of the heat pack was averaged to 540g.

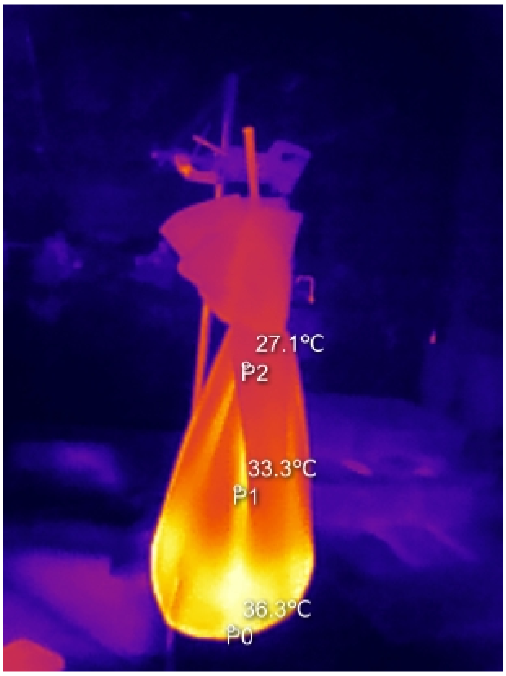

Figure 2: Thermal camera photo of experimental setup.

3.2 Conduction Results

Table 1: k value of different beanies and the individual qualities of each beanie.

	Composition	Colour	Bi-Layered	k-value (W/m·K)
1	50% Viscose 28% Polyester 22% Nylon	Black	No	0.075
2	50% Viscose 28% Polyester 22% Nylon	Light khaki	No	0.064
3	Outer: 52% Polyester 48% Acrylic Lining: 100% Polyester Filling: 61% Polypropylene (PP) 39% Polyester	Black	Yes	0.178
4	Outer: 54% Polyester 46% Acrylic Lining: 100% Polyester Filling: 61% Polypropylene (PP) 39% Polyester	Navy	Yes	0.201

Note that due to experimental error the temperature of the system increased over time, indicating energy generation. However, this is not true as there was no heat input and this most likely was a result of the exothermic reaction from the heat pack.

Conduction was calculated as it was predicted that the beanies with the smallest k values would be the greatest insulators as they limited heat transfer. This is dependent on the hot air from the heat pack conducting to the outer surface of the beanie. However, this assumes that all the beanies would experience conduction equally. This is only a valid assumption in beanie 1 and 2. For beanies 3 and 4, there were multiple layers, as per table 1. Although the polyester lining may have experienced conduction, the conducted heat was insulated by the second layer and filling as these layers were not one composite material. This could indicate that the surface temperature of beanies 3 and 4 are a greater reflection of the ambient temperature than the heat conducted by the heat pack.

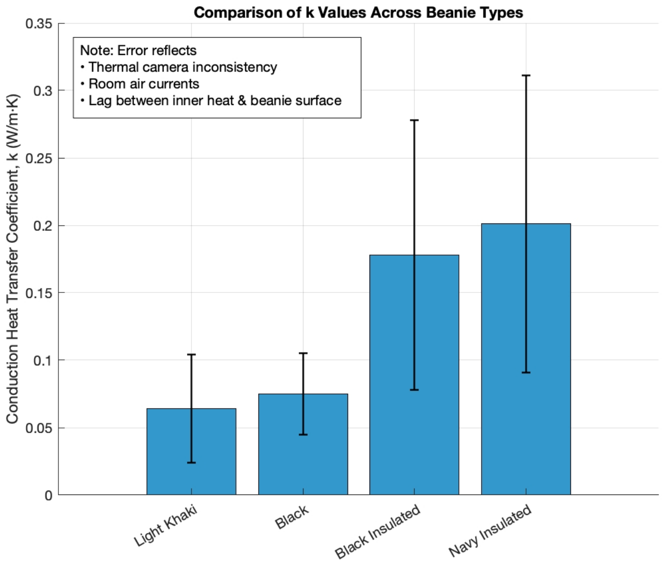

Figure 3: Bar chart of respective k -values with error bars.

Figure 3 is a graphical representation of the calculated k values and showcases the error bars for each k value. These error bars were calculated as the standard deviation for the k value of each beanie type of each repetition. Figure 3 indicates that the black beanie has the greatest replicability as the error of these calculations is smallest. These errors consider incomplete thermal contact, the air current of the rooms, the differing ambient temperatures and experimental error.

The paper's objective is to determine which beanie is most effective for heat insulation for the model 'head'. Therefore, there is a greater focus on heat retention within the beanie environment. As conduction is not a reasonable assumption for this experiment, a greater reflection of this trend is the change in temperature over the change in time.

As Figure 4 indicates, there is a steeper increasing temperature gradient for the insulated beanies in comparison to uninsulated. This solidifies previous assumptions that conduction may be an unreliable indicator within this experiment, and that the internal temperature of the heat pack may be more applicable to reflect real world conditions.

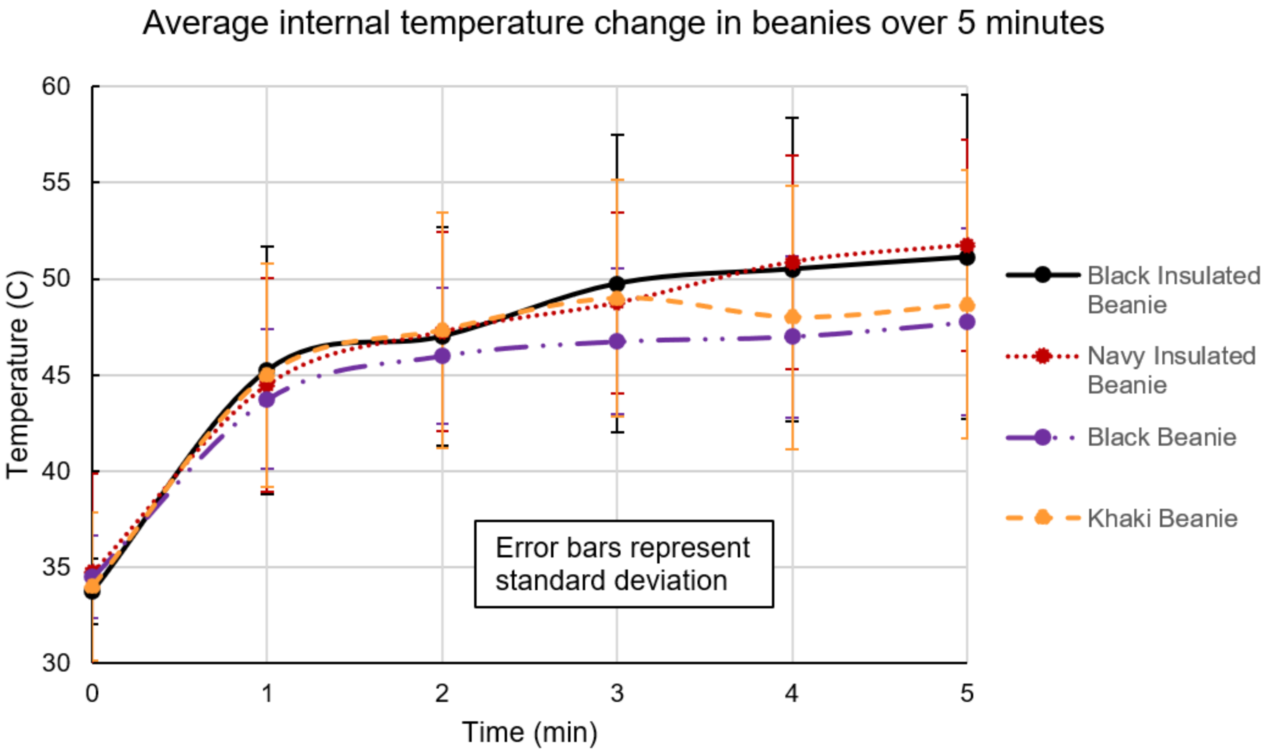

Figure 4: Internal temperature change in different beanies incorporating individual standard deviations.

3.3 Other Considerations

Interpreting the convection coefficients was also considered, however these results were not factored when considering which beanies were most effective. The convection coefficient considers the disparity between the beanie surface temperature and the ambient temperature.

However, this again assumes that the heat of the heat pack has transferred to the surface of the beanie. Biot number calculations, as found in appendix, indicate that all beanies had a Biot number far greater than 0.1. This indicates that convection dominates instead of conduction, however this is inaccurate in this scenario as thermal cameras over time indicate that some beanies had very little heat transfer from heat pack to beanie surface. Therefore, the thermal conductivity constant k is a better indicator of heat retention. For reference, the Biot number results and h-value coefficients can be viewed in appendix. The full scope of all numerical results can also be found via appendix.

4. Discussion

The purpose of this study was to compare the thermal retention capacity of four commercially available beanies under controlled laboratory conditions, using internal temperature change and thermal conductivity as comparative metrics. It was hypothesised that the black insulated beanie would be most effective in heat retention. As illustrated in Fig. 4, the insulated beanies retained heat more effectively over time compared to the uninsulated ones. The temperature drop in the uninsulated beanies was significantly faster, which indicates a lower capacity to resist heat loss. To quantify thermal performance, thermal conductivity (k) was calculated using a conduction-based approach. The black uninsulated beanie had the highest estimated value (k = -7.49 × 10-2 W/m·K), followed by the light khaki beanie (k = -6.43 × 10-2 W/m·K), both suggesting relatively poor insulation.

Although the insulated beanies showed lower thermal conductivity values navy (-20.1 × 10-2 W/m·K) and black (-17.8 × 10-2 W/m·K), these results should be interpreted with caution. Due to the internal layer of insulation creating pockets of air, the assumption of pure conduction does not apply. In such cases, the derived k-values might not represent purely conductive behaviour, but they were still included to fulfill the experimental requirement and to allow comparison under a consistent methodology. These observations underline the importance of considering the dominant heat transfer mode when interpreting calculated thermal parameters.

These results align with fundamental heat transfer principles, where materials exhibiting lower thermal conductivity typically offer higher thermal resistance. In the case of the insulated beanies, the dual-layer configuration, featuring a synthetic polyester lining beneath a knitted fabric, introduces air pockets that serve as barriers to both conductive and convective heat loss[9, 10]. While the calculated k-values for these samples should be interpreted cautiously, their observed thermal performance is consistent with findings from similar textile studies, where microstructural layering and trapped air significantly contribute to thermal retention[11– 14]. This effect is especially relevant in cold environments, where minimizing heat dissipation is essential for preserving core body temperature[1].

Several key findings emerged. The black insulated beanie did not perform as well as the navy insulated beanie, despite both sharing identical structure, thickness and very similar composition (refer to Table 1 above). There is uncertainty as to why the black beanie didn't perform as well as predicted, perhaps due to material properties, light reflection,or experimental error. Literature indicates that darker fabrics absorb and re-radiate more infrared energy[5], but their overall effectiveness as insulators also depends on weave tightness[15], fibre density[16] and internal air trapping capability[6, 11, 14]. It is likely that the shaded environment in which the experiment was conducted resulted in an inaccurate representation of the relationship between solar radiation absorption and colour of surface. Hence, the hypothesis of the black insulated beanie retaining more heat than the navy insulated beanie was not proved in this study, as colour of the fabric may not be a major factor in the indoor environment. To sufficiently investigate the effect of fabric colour on thermal warmth, a change to the method of experimentation, for example the addition of a controlled source of light, would be required. It is relevant to note that the colour of the beanie functions more in affecting thermal absorptivity, rather than thermal resistance.

Not all findings aligned exactly with theoretical expectations. A small yet noticeable increase in internal temperature was observed during certain observations, likely stemming from the exothermic nature of the heat packs used. Since no additional energy input occurred after placement, the apparent "heat gain" can be attributed to delayed equilibration between the heat pack and the surrounding air within the beanie. This may be alleviated by implementing a short, standardised waiting period in future experiments. The temperature gradient between the heat pack and the room likely required time to stabilise. Additionally, the delay in thermometer responsiveness likely skewed early temperature readings, introducing time lag errors that propagated across the measurement interval.

The observed inconsistencies in thermal conductivity values may also result from experimental uncertainty in beanie thickness measurements. The beanie was wrapped once around the heat pack as seen in Fig. 1 and Fig. 2. This was to create a near-spherical shape and thus imitate real-life conditions. However, the compressibility of fabric and shifting of silicone beads inside the pack likely altered the radius and the contact area during setup. These variables influence the conductive path length (δ) and surface area (A), which directly affect k-value calculations via Fourier's law. In future, it is recommended to use non-contact thickness sensors and 3D thermal imaging to minimize such uncertainties.

Ambient conditions also played a significant role. The experiment was conducted over two different days, with ambient room temperature varying between 22.3°C and 24.0°C. Although this variation seems minor, even small fluctuations in $T\infty$ can affect convective heat loss rates, especially when low-temperature gradients exist between the beanie surface and surrounding air. A tighter controlled test environment, such as performing all experiment runs in the same day, would improve reproducibility.

It is also important to consider the interplay between insulation and heat dissipation. Thicker fabrics usually keep the body warmer, but sometimes, the materials can increase heat transfer. This can happen if the fabric traps moisture, lets air pass through or creates more surface area for heat to escape, like how fins work in cooling systems[5, 12, 13, 17]. However in this experiment this was not observed: insulated beanies consistently retained heat better, indicating minimal fin effect. This follows theory as insulation reduces critical surface area for heat transfer - thermal insulation increases as the air gap between the body and the fabric increases, though beyond a gap of about 7.5–10 mm the thermal insulation decreases because of convection effects[18]. Scenarios involving external airflow (e.g., outdoor winter wear), affect this interplay and hence warrant further exploration[3, 6]. The effect is reportedly minimised in closely woven fabrics[18]

A factor to consider is the composition and knit weave type of the beanies. Non-insulated beanies did not include acrylic (generally more thermally insulating than polyester[19]) nor PP (the insulation material between the layers), whilst the insulated beanies did not contain any viscose, which provides stretch in the knit weave of the beanie. All materials are assumed to be synthetic, but any finishes or coating are not known. The differing composition and build between insulated and non-insulated beanie fabric affects stretch and porosity[20], critical surface area, moisture absorption[19], and heat resistance [19]. Furthermore, the k-values between beanie three and four could, but not conclusively, be attributed to the 2% more polyester content in the navy beanie's outer shell. If negating the factor of colour given the assumption that the experiment was conducted with little solar radiation impact, in literature, acrylic can trap moisture whilst polyester tends to be "moisture wicking" and relatively more breathable[19]. However, some research suggests that polyester fabrics, when layered, are very effective for heat retention (due to the air pockets created)[5, 9, 20]. Of particular importance, weave type of a knit fabric greatly affects thermal insulation [21] (which decreases as moisture increases) due to capillary action of the fibres facilitating moisture absorption[9, 18]. Coated fabrics can utilise moisture absorption qualities to consequently impact thermal insulation[18]. Literature suggests that moisture retention is one of the main factors affecting thermal conductivity of fabric[22] Due to the variety of polyester fabrics and their coatings, it would have been beneficial to understand what polyester is used to determine the effect of fabric composition and weave type on heat changes.

While this study did not provide definitive material rankings due to equipment-related variability and environmental influences, the relative comparisons between samples remain valid. Since identical methods were applied across all four beanies, consistent trends could still be observed and evaluated. Despite limitations such as potential thermometer delay and minor setup inconsistencies, the experimental arrangement was sufficiently controlled to yield meaningful insights into fabric insulation performance. The findings underscore how subtle experimental factors can influence thermal measurements and highlight the superior heat retention of insulated fabrics under the tested conditions. Future investigations could benefit from extending the observation period beyond five minutes and incorporating advanced techniques such as differential scanning calorimetry (DSC) or infrared thermography for more accurate quantification of heat flux. It is also relevant to investigate the thermal characteristics of knit fabrics made of natural materials that are not derived from petrol, such as yarn made from peat fibre[23], wool[24], or synthetic fibres combined with natural[25].

5. Conclusion

The hypothesis proposed in this study of the black insulated beanie exhibiting the highest heat conservation was only partially supported by the results of the experiment. Although the insulated beanies demonstrated superior heat retention, the black insulated beanie did not outperform the navy insulated beanie as predicted. This suggests that while insulation and fibre composition are key factors, colour was not a significant contributor to thermal retention under the indoor conditions tested. Overall, the study confirms that insulation and multi-layered construction significantly enhance thermal performance in everyday garments. However, inconsistencies in thermal conductivity calculations and internal temperature changes explained by methodological constraints such as delayed heat pack equilibrium indicate that conduction alone may not be a fully reliable indicator of insulation effectiveness in this context. Furthermore, factors such as moisture absorption and weave of the knit were not controlled or accounted for, and thus their impact upon results cannot be determined. Future experiments with refined measurement strategies and methodology, better environmental controls, and more suitable fabric samples would further isolate the influence of the factors of fabric composition and colour on thermal retention in domestic settings.

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Author Contribution Statements

A.K. performed calculations, extensively analysed results, created Fig. 2 and 3, Table 1, appendix and paper formatting. G.W. conceived the introduction, graphical abstract, and Fig. 3. M.Z. wrote the abstract, honed and wrote the methodology, created Fig. 1. R.S. further analysed and interpreted the results in depth, connecting to literature, in the discussion. A.Y. contributed to discussion, wrote discussion and formatted bibliography. All authors were involved in experiment methodology design and conducting the experiment, as well as reviewed and edited the manuscript. All tutors provided task direction and project assistance, and Dr. Gobinath Rajarathnam provided conceptual direction, research and writing guiding frameworks, facilitated project resources, and direct project supervision.

Competing Interests

Authors declare no competing interests.

Appendix

Appendix 1: Sample calculation using the insulated navy beanie. The mass of the heat pack was 0.54kg, estimated specific heat capacity 1250Jkg ×K, the beanie thickness was 0.008m and the radius of the heat pack as a sphere was 0.07. The below is for the navy beanie in repetition 1:

Using equation 1:

$$Q = mc\Delta T$$

$$Q = 0.54kg \times 1250 \left(\frac{J}{kg \times K}\right) \times (54 - 42)\,K$$

$$Q = 8100J$$

Heat per second over 5 minutes (300s):

$$Q = \frac{8100J}{300s} = 27W$$

Using equation 2:

$$A = 4\pi\,(0.07m + 0.008m)^2 = 0.076\,m^2$$

Using equation 3:

$$k = \frac{Q \times d}{A \times \Delta T} = (27W \times 0.008m) / (0.076\,m^2 \times (54 - 36.2)\,K = \frac{0.16W}{m \times k}$$

Appendix 2: Biot number results for each beanie

Beanie	Biot Number
1	2.36
2	2.55
3	3.42
4	2.39

Appendix 3: h-value results

$$h = Q / (A \times (T_{surface} - T_{ambient})$$

Where $A = 0.076\,m^2$, $T_{surface} = 32.65°C$, $T_{ambient} = 23°C$

$$h = (27W) / (0.076\,m^2 \times (32.65 - 23)\,K = 36.6\,\frac{W}{m^2 \times K}$$

Beanie	Average h-value
1	76.43
2	60.77
3	76.11
4	59.9

Appendix 4: Raw results for repetitions 1-4

Repetition 1	Intial	Column1	t=5	Column2	Column3	T=0	T=54
Time	middle	bottom	middle	bottom	average		
Control (heat with no beanie)	46	47.5	38.2	41.1	39.65	47.5	41.1
Light coloured	29	32.5	29.2	33.9	31.55	39	49
black beanie	33	36.3	30.1	36.3	33.2	35	47
black beanie w insul	28.1	35	27.2	29	28.1	37	54.5
navy beanie w insul	31.2	32.9	29.1	36.2	32.65	42	54
Repetition 2	Intial		t=5				
Time	middle	bottom	middle	bottom		T=0	T=5
Control (heat with no beanie)	48.3	40.8	42.3	33.7	38	48.3	42.3
Light coloured	28.3	33.1	30	35.4	32.7	33	56
black beanie	27.2	33.3	28.3	32.9	30.6	34	56
black beanie w insul	29.4	31	33.9	31.5	32.7	34	54
navy beanie w insul	29.8	33.2	30.3	34.1	32.2	34	52
Repetition 3	Intial		t=5				
Time	middle	bottom	middle	bottom		T=0	T=5
Light coloured	27.7	29.7	26.2	30.5	28.35	30	41
black beanie	27.5	31.5	27.2	33.2	30.2	33	46
black beanie w insul	30	25.5	29.6	27.7	28.65	34	53
navy beanie w insul	27.3	35.1	27.6	32.9	30.25	33	55
Repetition 4	Intial		t=5				
Time	middle	bottom	middle	bottom		t=0	t=5
Light coloured	27.5	32.1	27.3	31	29.15	36	42
black beanie	26.8	28.5	27.2	31.5	29.35	30	46
black beanie w insul	29.8	26.7	29.1	28.7	28.9	33	37
navy beanie w insul	29.4	30.2	34.4	30.9	32.65	30	43