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An investigation into the role of skin biophysics and fluid thermal properties in underarm wetness perception with applications to antiperspirant deodorants

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by

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Abstract

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By Jade Ward

Sensing wetness on the skin plays a fundamental role in supporting human homeostasis by influencing thermal discomfort, behavioural responses, and autonomic thermoregulation. However, the skin lacks dedicated hygroreceptors; instead, wetness is thought to be a learnt sensory experience, arising from repeated exposure to wet stimuli. When moisture is present on the skin, a complex integration of multisensory inputs occurs, primarily involving thermal cues generated by heat transfer and evaporation, combined with tactile cues such as pressure and friction. Together, these inputs create the subjective experience of wetness.

Beyond its evolutionary significance, wetness perception is also important for product comfort and acceptability, particularly during the application of antiperspirant deodorants. The underarm has unique biophysical characteristics, including hair coverage, high sweat gland density, and variations in stratum corneum hydration, which may impact sensory response. During application, users may experience transient, unwanted sensations of wetness arising from product movement across the skin and thermal exchange between the formulation and the skin surface. Despite the industrial and sensory relevance of this interaction, neither the underarm region nor antiperspirant formulations have been systematically investigated within the field of wetness perception.

Following a comprehensive literature review, a series of controlled experimental studies were conducted using modulated external wet stimuli via a temperature-controlled probe to the underarm. These studies were designed to isolate and replicate key components of antiperspirant application (i.e. time-dependent changes, Chapter 6 - 8), user hygiene routines (i.e. the presence and removal of hair [Chapter 5] and skin hydration [Chapter 4 and Chapter 8]) and fluid formulation (i.e. thermal conductivity, Chapter 6 - 8) to understand the mechanisms of the skin-moisture interactions.

Collectively, this PhD demonstrates that wetness perception at the underarm is governed by an interaction between skin biophysical properties (hydration state and hair coverage) and the thermal properties of applied fluids, mediated primarily by changes in skin cooling. Established wetness mechanisms were confirmed at the underarm, with cold-wet stimuli perceived as wetter and overhydration amplifying wetness during cold contact. Underarm hair was shown to influence wetness, acting as a barrier during static contact while enhancing tactile contributions during dynamic interactions. Methodologically, the development of a continuous wetness perception test enabled quantification of the temporal dynamics of wetness with integrated skin temperature responses, revealing that the rate and magnitude of skin cooling—rather than fluid thermal properties alone—drive wetness perception differences. Together, these findings established and refined a time-dependent model of wetness perception, in which temperature-driven experience is shaped by local biophysical characteristics and fluid thermal properties. Collectively, these results can inform the design of antiperspirant deodorants for improved comfort upon application.

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Research Thesis: Declaration of Authorship

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I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

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- **Ward, J.,** Verucchi, E., Swaile, D., Parker, K., Worsley, P., Filingeri, D. (2025). The effects of stimulus temperature and skin hydration levels on wetness perception at the underarm. Skin Research and Technology, 31, 2-5. https://doi.org/10.1111/srt.70170

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Definitions and Abbreviations

P&G ..... Procter and Gamble

WP..... Wetness perception

SCH ..... Stratum corneum hydration

Tsk..... Skin temperature

APDO..... Antiperspirant deodorants

QST..... Quantitative sensory test

VAS..... Visual analogue scale

TRP ..... Transient receptor potential

AUC ..... Area under the curve

T2R ..... Time to respond

T2R post..... Time to respond post contact

T2P ..... Time to peak

T2B ..... Time to baseline

PG ..... Propylene glycol

MO ..... Mineral oil

PMX ..... Dimethicone

PEG ..... Polyethylene glycol

Blend ..... 50/50 water/polyethylene glycol

OCT ..... Optical coherence tomography

c-WPT..... Continuous wetness perception test

SPSS..... Statistical package for the social sciences

CI ..... Confidence intervals

SD ..... Standard deviation

SEM ..... Standard error of measurement

PCA ..... Principal component analysis

PC ..... Principal components

ICC ..... Intraclass correlation coefficients

MDC ..... Minimum detectable change

FA..... Fast adapting

SA..... Slow adapting

Publications

Ward, J., Verucchi, E., Swaile, D., Parker, K., Worsley, P., Filingeri, D. (2025). The effects of stimulus temperature and skin hydration levels on wetness perception at the underarm. Skin research and technology, Skin Research and Technology, 31, 2-5. https://doi.org/10.1111/srt.70170

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Ward J, Swaile D, Parker K, Cochran B, Caggiari S, Worsley P, Filingeri D. The impact of stratum corneum hydration on underarm wetness perception during contact with fluids varying in thermal conductivity. *International Union of Physiological Sciences,* 11 – 14 September 2025, Frankfurt, Germany. *Poster Presentation.*

Ward J, Martin J, Swaile D, Parker K, Cochran B, Caggiari S, Worsley P, Filinger D. The impact of hair on local skin wetness perception at the underarm during static and dynamic applications of cold-wet stimuli. *The Physiological Society,* 3 – 4 June 2025, Brunel, UK. *Poster Presentation.*

INVITED TALKS

Invited speaker: Procter and Gamble Research and Development HQ, Cincinnati, USA, October 2025: In-person presentation on 'The Physiological and perceptual mechanisms of skin wetness sensing at the underarm'

Invited speaker: Channel 4 TV Show 'What's the big deal?', April 2025: 'What is sweat and why do we sweat…antiperspirants vs deodorants'

Invited speaker: BBC Radio World Services show 'Crowd Science', February 2025: 'is water wet?'.

Invited speaker: University of Southampton, UK, November 2024: School of Psychology seminar series 'Centre of Perception and Cognition'

AWARDS

Competitive Early Career Researcher Workshop- The Physiological Society 2023

- Competitively selected (only 2 awarded out of 15 applications) to undergo intensive research training in methods to investigate individual variability in physiological responses in humans, which led to an invited talk at The Physiological Society UK's workshop on "Variability, Physiological Variability, and Individual Responses".

Doctoral College Research Awards – University of Southampton 2025

- Competitive prize awarded for outstanding academic performance and academic achievement within the School of Health Science

Chapter 1 Introduction

1.1 Research Motivation

Antiperspirant deodorants are commonly applied daily to the underarm to minimise sweat and odour production via the sweat glands (Martini, 2020). Body odour is associated with poor personal hygiene, which can affect both self-esteem and how an individual is perceived in society (Martini, 2020, Oliveira et al., 2021). The chemical engineering of antiperspirant deodorants for sweat mitigation is well researched and reasonably understood. Yet, antiperspirant deodorants are not fully effective at limiting sweat secretion onto the skin (Martini, 2020). The production and accumulation of thermal and psychogenic sweating onto the skin increases wetness perception, which in turn can lead to an increase in thermal discomfort, and changes in behavioural thermoregulation (Fukazawa and Havenith, 2009).

In addition, negative thermal comfort has been experienced when an external wet stimulus contacts the surface of the skin, such as a wet fabric (Filingeri et al., 2014b). Thus, the physical action of applying an antiperspirant product to the skin may trigger these undesired wet perceptions, affecting thermal comfort and product satisfaction. Although much is known about how humans perceive skin wetness across various regions of the body, little has been done to explore the mechanisms of wetness at the underarm. This is despite its direct link to antiperspirant deodorant product research and development to ensure consumer acceptability, whilst experiencing a ‘cool and refreshing’ rather than ‘wet and sticky’ sensation during application (Hazell, 1999).

Furthermore, the chemical formulation of an antiperspirant will change legally by 2027, with a key silicone removed from the formulation, due to new regulations on sustainability and biodegradability (Agency, 2020). Yet this commonly used fluid is known for its quick-drying effect and smooth feel. With this removed, increased wetness perception may be experienced upon product contact with underarm skin. Therefore, to enhance product development in line with this change, while ensuring consumer satisfaction is maintained, the mechanisms by which wetness is experienced at the underarm requires investigation.

The study of humans’ ability to detect the presence of wetness on the skin has grown in interest over the last century. During the early 1900s, Bentley demonstrated that the perception of wetness (known as liquidity in his research) was experienced through the combination of touch and temperature stimuli at the skin, but more specifically during the touch of cold temperature stimuli. Following this observation, more recent research has demonstrated that wetness is a learnt experience through a complex multisensory interaction between the skin and external

moisture, specifically thermal (i.e. heat transfer) and tactile (i.e. mechanical pressure and friction) cues, that ultimately lead to the conscious experience of skin wetness (Bergmann Tiest et al., 2012, Filingeri, 2014). However, there is a significant lack of experimental studies specifically investigating wetness perception at the underarm and how its unique biophysical properties (i.e. hair and skin hydration) play a role in experiencing the perception of skin wetness.

Moreover, the vast majority of wetness perception research has investigated the external application of a wet stimulus during short-duration (~10 s) contact (Merrick et al., 2021, Valenza et al., 2019, Ackerley et al., 2012). Whilst important for identifying the role of thermal and tactile cues in the initial wetness experienced for enhancing fundamental knowledge. There is a need to understand how the perception of wetness varies over time during extended contact (> 10 s) with an external wet stimulus and how this perception might change based on the fluid being applied (i.e. water vs silicone). This would provide novel insight into the mechanism of skin biophysics and the fluid properties in the role of a temporal wetness perception. On the applied side, this could be useful for the potential development of a continuous wetness methodological assessment, which replicates a real-world scenario, such as applying an antiperspirant deodorant for improved product testing, formulation design and consumer perceptual awareness.

This thesis investigates the mechanisms of wetness perception at the underarm during the application of an external wet stimulus, with focus on the role of the biophysical properties of the skin (hairiness and skin hydration) and fluids (water vs silicone) varying in thermal properties. This will contribute to a better understanding of the physiological and perceptual mechanisms that contribute to skin wetness perception at the underarm during interactions with various fluids for the innovation of antiperspirant deodorant design during product application.

This PhD is fully funded by Procter and Gamble (P&G), an American multi-national consumer goods company and manufacturer of antiperspirant deodorants.

Chapter 2 Literature Review

A literature review was carried out to evaluate the current research investigating the mechanisms of wetness perception at the underarm during the application of an external wet stimulus, with focus on the role of the biophysical properties of the skin and thermal properties of fluids. This literature review firstly aimed to summarise our current understanding of wetness perception and antiperspirant deodorants. This was followed by a more focused narrative review on the unique biophysical characteristics of the axilla and research and development challenges for antiperspirant application, which aimed to achieve the following objectives:

1. To critically evaluate how biophysical properties of the underarm, such as hairiness and stratum corneum hydration, and thermal properties of a fluid may impact wetness perception during external stimuli application.
2. To identify knowledge gaps on the mechanisms and current methodologies to evaluate wetness perception at the underarm, which may impact the application of antiperspirant deodorants.

A structured narrative literature search was conducted to identify relevant research examining wetness perception and the interactions of biophysical properties of the skin and thermal fluid properties for comfort during antiperspirant application. Searches were performed across multiple electronic databases, including PubMed, Google Scholar, Scopus and Web of Science. Search terms were developed iteratively based on the research aims and combined using Boolean operators. Key concepts were used selectively based on the objectives cited above and included: wetness perception, antiperspirant deodorants, axilla, tactile sensation, thermal sensation, thermal comfort, behavioural thermoregulation, thermal conductivity and heat capacity, structure and functions of the skin, sensory receptors, hair follicle, stratum corneum hydration, static and dynamic stimuli application, antiperspirant chemical formulation, somatosensory system, continuous psychophysics and quantitative sensory testing, skin temperature, material discrimination and, heat transfer. These terms were combined using operators such as AND OR to refine results (e.g. wetness perception AND axilla AND antiperspirant deodorant; Tactile sensation AND stratum corneum hydration AND wetness perception).

2.1 Antiperspirant Deodorants

2.1.1 Overview and Mechanisms of Action

Experiencing wetness on the skin as a result of sweating or contact with fluids has been repeatedly shown to induce thermal discomfort, which is a critical trigger of behavioural responses in humans (Gagge, 1937, Filingeri and Havenith, 2018). Consider, for example, the common experience of wetness at the underarm resulting from thermal or psychogenic sweating. Millions of people apply antiperspirant deodorant (APDO) products to the underarm on a daily basis to minimise this negative experience (Watkinson et al., 2007).

APDO are consumer goods hygiene products applied on the underarm to fight odour, reduce sweating and increase self-confidence (Teerasumran et al., 2023). Inefficiencies of antiperspirant action or a lack of application can create visual sweat stains or noticeably wet skin, all of which may negatively impact a person's quality of life (Swaile et al., 2012). Sweat is secreted at the underarm through three different sweat glands, eccrine, apocrine and apoeccrine (see 2.2.2.1) (Sato et al., 1987, Shelley and Hurley, 1953). The fluid secreted from each type of sweat gland varies based on its functional properties, which, when bacteria residing in the underarm react with, results in malodour (Low, 2012).

APDO have become well-established worldwide and are available in many physical forms and chemical formulations, such as roll-ons, aerosols, creams, sticks and gels (Benohanian, 2001).

Irrespective of product type, APDO have four essential ingredients (Teerasumran et al., 2023);

1) Antimicrobial agents such as propylene glycol and sodium bicarbonate,

2) Fragrances such as linalool found in many flowers and spice plants,

3) Odour absorbers such as zinc carbonate and talc,

4) Acidifiers to reduce pH, such as aluminium-zirconium compounds.

The mechanisms of APDO are through two actions: reducing the amount of perspiration from the eccrine glands, and second, by inhibiting bacterial growth (Abrutyn, 2021). The aluminium-based salts are transported to the opening of the eccrine sweat glands, interacting with the proteins and dissolving to form a blockage or gelatinous plug, preventing sweat from emerging onto the surface of the skin (Figure 1), limiting contact with bacteria and keeping the underarm dry (Abrutyn, 2021, Swaile et al., 2012, Teerasumran et al., 2023, Pariser and Ballard, 2014). Although it should be noted that the effectiveness is limited to the formulation of the product, which achieves 80% efficiency in plugging all the glands, with a washout period of around one to

two weeks before the plug is pushed out, and the glands can operate as normal again (Abrutyn, 2021, Draelos, 2001).

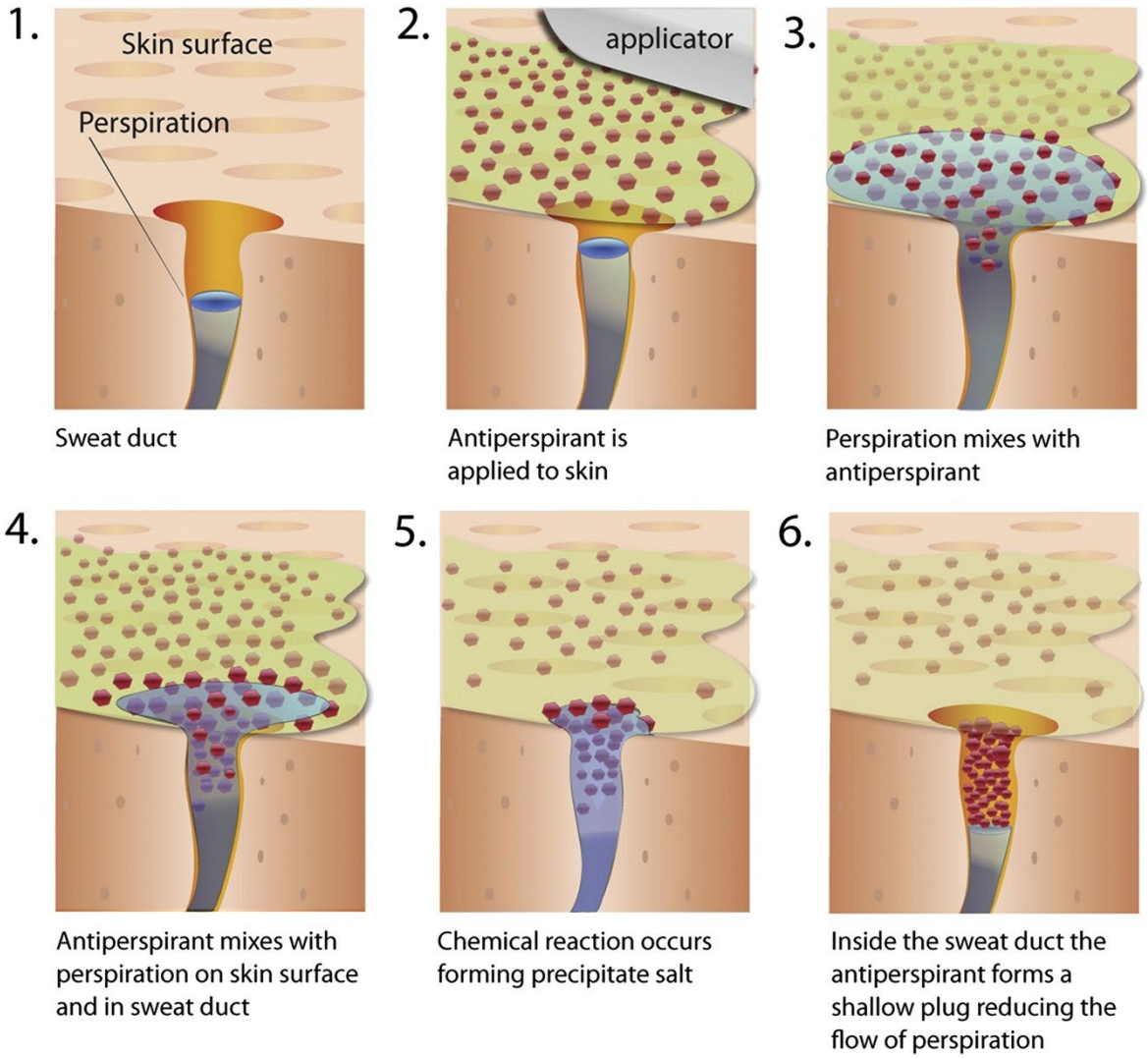

Figure 1. Schematic of the mechanisms of antiperspirant deodorant actions. Reprinted with permission from (Pariser and Ballard, 2014).

APDO products are categorised into different application forms, such as roll-ons, aerosols, stick / soft solids and clear gels, each with its own benefits and formulating challenges. The formulation of product delivery is the key to the effectiveness of APDO performance and consumer acceptance (Abrutyn, 2021) (Figure 2). Products are bought based on a user's previous application experience, such as leaving residue on the skin, feeling dry on application, or based on their daily hygiene habits (i.e. applying after a shower) (Hazell, 1999). A product's success is based on its effectiveness to reduce sweat, through a wetness-inhibiting performance test and body odour sniff tests, over a 24 - 48 hour period (Abrutyn, 2021,

Bleckwenn et al., 2018, Schmidt-Rose et al., 2013) and verbal consumer perceptual feedback during product application (Abrutyn, 1998). Hazell (1999) established differences in product application sensations, such as aerosols, which were described as feeling cool and refreshing, whereas roll-ons were perceived as slow-drying, wet and sticky. However, the avenues of the qualitative data collection were not mentioned, nor were any links made to the mechanisms that might underpin these sensory experiences during different product applications.

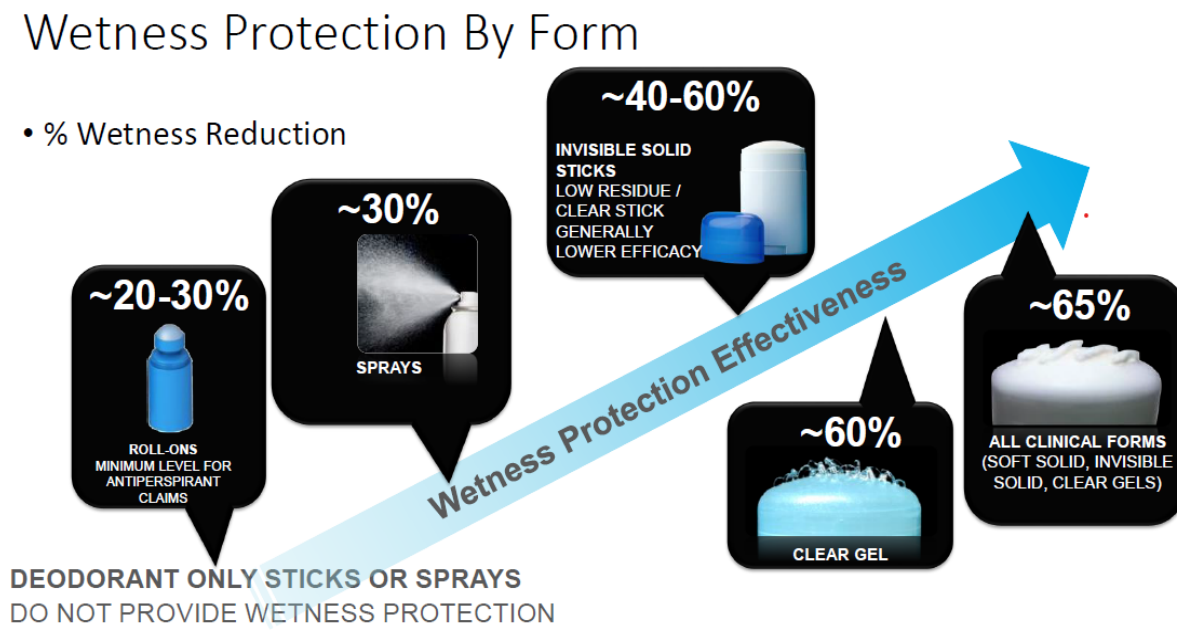

Figure 2. Schematic of the various antiperspirant deodorant products and their effectiveness for wetness protection. Reprinted with permission from (Procter and Gamble, 2022).

2.1.2 Research and Development Challenges

Whilst APDOs are generally effective in limiting sweat-induced wetness at the underarm (Teerasumran et al., 2023), these products can trigger undesired wetness perceptions at the point of application, that is, when a 'wet' product at room temperature (~23 °C) contacts the skin of the underarm (which has a likely temperature of ≥ 34 °C). This 'acute' wetness experience may negatively impact the acceptability and comfort of such products. There is a paucity of evidence regarding the application-induced wetness with respect to users' comfort, despite its recognised importance. Hence, an increased understanding of the mechanisms of wetness perception at the underarm upon contact with an external wet stimulus could inform the design of a more thermally comfortable APDO. However, there are several current research

and development challenges in the APDO market that apply to the afore-mentioned application scenario.

APDO are formulated to deliver active ingredients effectively while providing a dry and thermally comfortable sensation upon application. Volatile silicones, such as cyclomethicones, have traditionally been incorporated into formulations because they evaporate rapidly with minimal associated skin cooling, thereby helping to reduce perceived wetness during use (Abrutyn, 1998). However, regulatory restrictions on certain dimethylcyclosiloxanes, driven by environmental concerns, have required their removal from APDO products by 2027 (Agency, 2020). As these fluids may contribute to limiting heat transfer from the skin and minimise the associated cooling, their replacement raises concerns regarding increased evaporative cooling during application and, consequently, greater perceived wetness and reduced thermal comfort. Insight can be leveraged from material discrimination studies, as changes in skin temperature underpin object and material discrimination through the interaction of physical, perceptual, and cognitive processes (Figure 3). Physically, heat flows from warmer to cooler objects until equilibrium is reached (Guo et al., 2007, Wang et al., 2023). Perceptually, humans detect these temperature changes via thermal sensitivity, and cognitively classify materials based on learned associations—such as identifying metal as colder than wood because it extracts heat from the skin more rapidly (Ho, 2018). This interaction is governed by material thermal properties, particularly thermal conductivity (the rate of heat transfer) and heat capacity (the energy required to change temperature) (Bergmann Tiest et al., 2012, Kazemi et al., 2025, Salazar, 2003, Ho, 2018). As APDO formulations contain fluids with differing thermal properties, they may alter skin cooling during application, shaping perceptions of “cool and refreshing” versus “wet and sticky” (Hazell, 1999). Furthermore, Guest et al. (2012) investigated the influence of fluid rheology on sensory perception at the forearm and underarm using fluids including silicones, deodorant, wax, and oil. Greater fluid viscosity at low shear rates was associated with perceptions of coldness and wetness, whereas high shear rates were associated with greater perceived thickness. Site differences were also observed, with forearm application perceived as more lubricating, silken, comfortable, and less textured than the underarm. However, the authors noted that the mechanisms underlying these site-specific perceptual differences remain unclear, potentially reflecting variations in skin properties such as epidermal thickness and receptor density. Further investigation may provide valuable insight into how fluid formulation influences wetness perception, comfort, and product acceptability.

Skin wetness has long been associated with increased thermal discomfort (Gagge et al., 1967), and a substantial body of research has demonstrated that wetness perception is primarily driven by local skin cooling rather than direct detection of moisture (Bentley, 1900, Tiest et al., 2012, Fukazawa and Havenith, 2009, Filingeri et al., 2014b) (see 2.4). When moisture contacts

the skin, such as during the application of an APDO, heat exchange and evaporation reduces local skin temperature, and elicits greater magnitudes or rates of cooling associated with larger wetness sensations (Filingeri et al., 2013b). Therefore, necessary modifications to APDO formulations may alter the thermal properties of the applied fluid, influencing skin cooling and, in turn, the perceived dryness and thermal comfort experienced by consumers during application. Despite the well-established role of skin cooling in wetness perception across several body sites, the extent to which these mechanisms operate at the underarm remains poorly understood. The axillary region represents biophysically distinct characteristics, i.e. variable microclimate, hair coverage and stratum corneum hydration (SCH) changes (Evans et al., 2012), all of which may influence heat transfer and multisensory integration (see 2.2). Addressing this knowledge gap is therefore essential to establish the underlying determinants of wetness perception at the underarm and to provide an evidence-based understanding for future APDO design that optimises perceived dryness and thermal comfort during application.

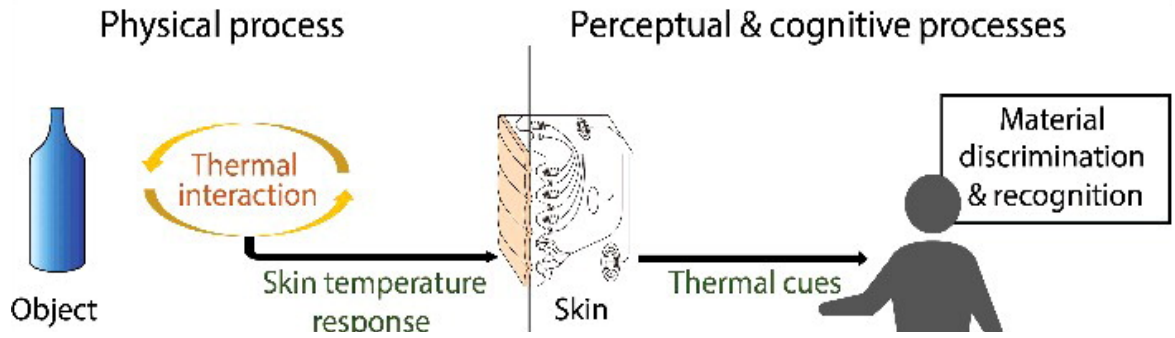

Figure 3. Physical, perceptual, and cognitive processes involved in material recognition based on thermal cues. Reprinted with permission from (Ho, 2018).

A further research and development challenge is in regard to the current methodology to assess wetness perception, which does not replicate a real-world scenario of applying the product to the skin (see 2.4.4). Most studies that capture wetness use a single time point assessment (~10 s), limiting our understanding to the initial response or first experience of wetness rather than the realistic skin-moisture interactions (beyond ~10 s). In reality, wetness perception likely evolves over time as biophysical and perceptual responses adapt. For example, following initial contact, skin cooling occurs, and wetness is first perceived. With repeated application, the magnitude of skin cooling and perceived wetness may increase before stabilising during sustained contact. After product removal, the skin begins to rewarm, and perceived wetness gradually declines. Without an assessment to evaluate the time-dependent changes in wetness

perception and its interaction with evolving skin temperature, the real-life experience of wetness perception during APDO application has yet to be fully understood.

Addressing these research and development challenges requires consideration of the unique anatomical and physiological characteristics of the axilla, as the sensory experience during application is ultimately shaped by the properties of the skin to which the product is applied. The underarm is not a typical test site used in wetness perception research, yet it presents distinct structural and functional features, including dense hair coverage, a high concentration of sweat glands, and variable SCH. These factors are likely to influence heat transfer, mechanical interaction and multisensory integration of thermal and tactile cues. Consequently, understanding the structure and function of the axilla is essential to determine whether established wetness mechanisms derived from other body regions can be directly applied to this site, or whether axillary-specific responses must be considered in future APDO design.

2.2 Axilla

The underarm, or axilla, is a pyramidal anatomical region between the upper limb and the lateral thoracic wall (Gordon and Alsayouri, 2025). The skin of the axilla is characterised by a high density of sweat glands (eccrine, apocrine and apoeccrine), hair follicles and has a relatively warm, humid microclimate. The unique skin site of the underarm undergoes various mechanical and structural changes as it is subject to various hygiene routines, such as repeated hair removal and APDO application, which may compromise the skin's barrier function, contributing to the protective properties of the uppermost layer of the skin, the stratum corneum (Evans et al., 2012).

Shaving, in particular, has been associated with sensory irritation and skin damage resulting from premature removal of corneocytes within the uppermost layers of the skin, leading to epidermal thickening and reduced hydration relative to unshaved skin (Turner et al., 2007, Evans et al., 2020). However, this evidence is obtained from female-only cohorts, limiting its generalisability to males, given known sex- and age-related differences in skin structure (Rahrovan et al., 2018). Sex differences have been reported in underarm surface area, with males exhibiting noticeably larger axillary surface areas than females (271 vs. 129 cm^2) (Cowan-Ellsberry et al., 2008). Consequently, when equal amounts of APDO are applied, females receive a greater product amount per unit area (Cowan-Ellsberry et al., 2008), which may influence sensory perception. Given the smaller axillary surface area in females, a greater proportion of the skin may be stimulated during product application (i.e., wet stimulus

exposure), potentially enhancing sensory responses, such as thermal discomfort. Supporting this notion, females have been shown to exhibit greater sensitivity to thermal and wetness stimuli across multiple body regions (Valenza et al., 2019). The study proposed that enhanced female sensitivity could be due to a greater proportion of the skin being stimulated, thereby resulting in more thermosensitive afferent nerve activation, compared to males. Yet, there is limited understanding of the sensory and biophysical features of the underarm that could influence wetness perception. Below, a more detailed explanation of the structure and function of the axilla is provided to explore how this region responds to thermal and wet stimuli.

2.2.1 Structure of the Axillary Skin

The skin is the largest sensory organ in the human body, providing an interface between the external environment and internal functions (Gerhardt et al., 2008). The skin's complex structure can be divided into three layers: epidermis, dermis, and hypodermis (Figure 4). These layers contain primary components of a multilayered stratified epidermis, adnexal structures such as hair follicles, sweat glands, nerve fibres, and neurovascular bundles (Lai-Cheong and McGrath, 2021).

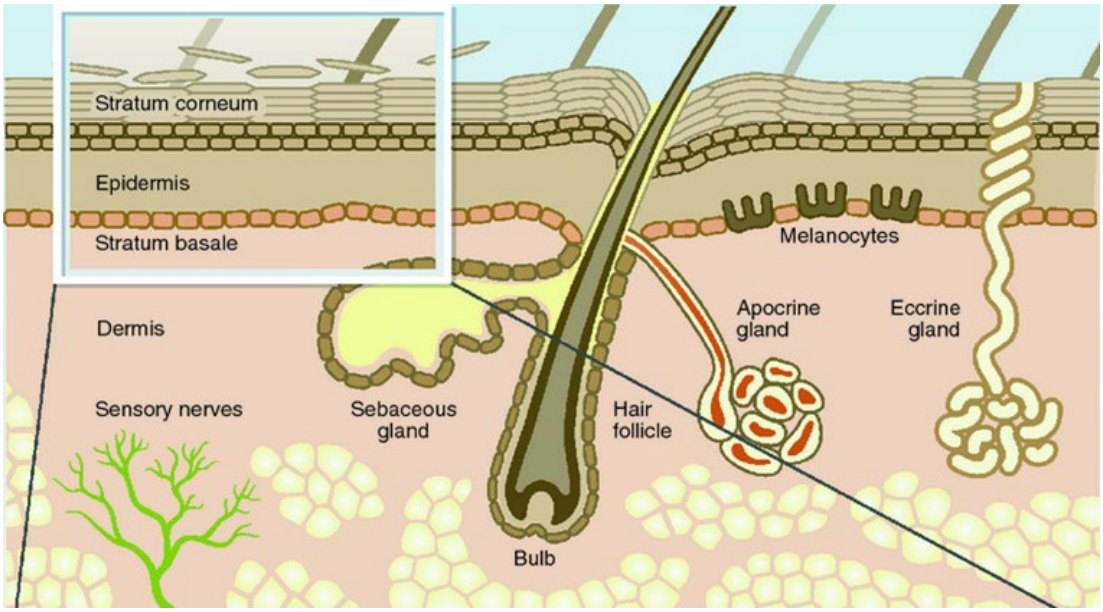

Figure 4. A schematic of the structure of axillary skin, comprising appendages: the hair follicle, the eccrine and apocrine sweat gland, the sensory nerves and the individual layers of the skin, including stratum corneum. Reprinted with permission from (Evans et al., 2012).

2.2.1.1 Epidermis

The epidermis is the topmost layer, which can be divided into five strata. The deepest of these is the region in which the keratinocytes are located. These cells can proliferate, taking about a 40-day cycle, which ends in the formation of the stratum corneum (Lai-Cheong and McGrath, 2021). Other cell types within the five layers include Melanocytes, which synthesise melanin for colour pigmentation; Langerhans cells, which are responsible for immune response; and Merkel cells, which transmit sensory information from the skin to the sensory nerves (Bader and Worsley, 2018).

There are great regional variations in the thickness of the epidermal layer. The hairless skin of the palms and soles is thickest (~1.5 mm) due to an extra layer of epidermis (Yousef et al., 2017). Conversely, there have been reports of higher epidermal thickness at the underarm with differences amongst regions, centre (~3.1 mm), compared to the peripheral (~1.8 mm) (Trindade de Almeida et al., 2025, Lintzeri et al., 2022). Although the majority of recruited participants were females, the shaving habits were not controlled for, which is known to thicken the epidermis (Evans et al., 2020, Turner et al., 2007). This is supported by a study that observed similarities in epidermal thickness between the shaven bearded area for men and the shaven centre of the female axillary (Turner et al., 2007). They concluded that frequent shaving induced hyperproliferation and local thickening to facilitate the repair of barrier function to enhance protection for subsequent shaving events. The thickening of the epidermal layer may alter the mechanical properties of the skin, which may dampen tactile sensitivity during stimulation (Sakaguchi et al., 2024, Liu et al., 2015), which is particularly important from a wetness perspective, as our perception arises from the integration of thermal and tactile cues (Filingeri et al., 2015c). Therefore, epidermal thickening may dampen mechanical input, potentially reducing the tactile component of wetness perception and altering the perceived sensation. This is relevant for APDO applications as the product may feel more thermally comfortable for habitual shavers, due to the potential dampened tactile inputs, yet evidence for this is limited.

2.2.1.2 Stratum Corneum

The most superficial layer of the five strata of the epidermis is the stratum corneum, which consists of 15–20 layers of dead corneocytes, which shield the body from excessive water loss or absorption (Wang et al., 2019, Yousef et al., 2017). The stratum corneum skin barrier traditionally has been described as a brick-and-mortar structure, the bricks representing the corneocytes and the mortar being the lipid bilayers (Elias, 1983). When exposed to watery solutions, such as during a shower, corneocytes instantly consume and absorb the water,

leading to epidermal hydration and swelling (Yousef et al., 2017). Considerable differences in the uptake of water absorption have been seen between the hairy skin site of the forearm and the glabrous fingertip (Verrillo et al., 1998), with the greatest uptake and retention in hairy skin. This appears to relate to the thickness of the epidermal layers in the glabrous skin, and the presence of hair may help permit easy penetration into the epidermis (Verrillo et al., 1998). These water-related cellular changes in the stratum corneum alter the chemical structure and mechanical properties of the skin, such as an increase in skin surface area (Gerhardt et al., 2008). Research has found a positive correlation between total skin thickness and stratum corneum thickness, and highlights that it is a critical factor in determining water content (Serup et al., 2006). Water content imparts suppleness, elasticity, flexibility and softness of the skin (Barel and Clarys, 2006).

SCH is influenced by age, sex, anatomical region, circadian rhythm, and habitual cosmetic use, reflecting underlying morphological and functional differences across skin sites (Samadi et al., 2022, Camilion et al., 2022, Gerhardt et al., 2008). Notably, males exhibit higher SCH than age-matched females up to approximately 40 years of age (Samadi et al., 2022). Increasing skin hydration also induces sex-specific mechanical changes, which demonstrate that females showed greater sensitivity to hydration than males, which was attributed to softening of the skin and expansion of the contact area (Gerhardt et al., 2008). Functionally, elevated skin hydration reduces the perceived roughness of textured surfaces on the fingertip (Verrillo et al., 1998, Lévêque et al., 2000), likely due to stratum corneum swelling increasing the number of effective contact points. Given that males generally present with higher baseline skin moisture, it has been suggested that they may perceive surfaces as less rough than females, although perceptual outcomes were not broadly considered in the study (Verrillo et al., 1998). More recent experimental evidence further supports the mechanistic link between SCH and tactile sensitivity. Sakaguchi et al. (2024) demonstrated in a randomised controlled trial that experimentally increasing SCH via a moisturising cream enhanced tactile discrimination, which was directly associated with increased skin displacement under mechanical load.

Furthermore, a comparable model is aged skin, which shares characteristics with dehydrated skin and exhibits up to a 78% reduction in hydration across body regions (Wildgoose et al., 2021). Older adults demonstrated a reduction in wetness perception during warm-, neutral-, and cold-wet stimulus contact compared with younger individuals, despite maintaining typical thermal sensitivity patterns (i.e., cold-wet perceived as wetter than neutral or warm-wet). This suggests that hydration-related changes in skin properties, in this case due to age, underlie altered wetness perception, rather than thermal sensitivity (Wildgoose et al., 2021, Guergova and Dufour, 2011). Collectively, these findings may suggest that hydration-induced alterations

in skin mechanics might modulate thermal and tactile inputs. Whether similar hydration-related effects occur at the underarm remains unknown.

Given that wetness perception arises from the integration of tactile and thermal inputs, these findings raise the question of whether alterations in SCH modulate wetness sensitivity. While increased hydration may enhance mechanical interaction and alter tactile signalling, the direction of its influence on perceived wetness remains unclear. Importantly, existing research has predominantly focused on the fingertip and hairy regions such as the forearm, yet the effects of hydration-induced changes at the underarm remain unexplored. The axillary's stratum corneum undergoes dynamic fluctuations in hydration due to sweating, showering, APDO application, and circadian variation, yet it is unknown whether these variations influence the perception of externally applied wet stimuli. To date, no studies have examined how the modulation of SCH at the underarm may affect wetness perception, nor whether sex-specific differences contribute to perceptual variability at this site.

2.2.1.3 Dermis

Below the epidermis lies the dermis, which mainly contains collagen, a structural protein that maintains elasticity, sensory nerves, a microvascular network, sweat glands, and hair follicles (Vestita et al., 2022, Yousef et al., 2017). Moreover, a series of strategically distributed sensory nerve endings migrate parallel to the surface from the deep dermis, namely touch and pressure (mechanoreceptors), pain (nociceptive) and temperature (thermoreceptors, see 2.2.2.3) (Parsons, 2007).

Embedded within this dermal layer are the skin appendages, most notably the sweat glands, which are highly concentrated in the axilla. These glands, together with hair follicles and associated sebaceous structures, contribute to the axilla's unique microenvironment, potentially influencing the sensory experience of wetness at this skin site.

2.2.2 Skin Appendages

2.2.2.1 Sweat Glands

Sweat glands were discovered in 1833 by Purkinje, and it was originally thought that there were two different types of human sweat glands, apocrine and eccrine glands (Shelley et al., 1953). However, in 1987 a third type of sweat gland, the apoeccrine gland, was established by Sato et

al. (1987) (Figure 5). Sweat glands are cutaneous appendages, like hair follicles and are exocrine as they secrete sweat via a duct to the outer skin surface (Wilke et al., 2007).

Apocrine and eccrine glands can be categorised by their morphology, whereas the obvious structural differences are much more complicated to discriminate for apoeccrine glands. Sweat glands begin to develop during the third month of an embryo, growing from the epidermal ridge, becoming fully developed, equivalent to that of adult sweat glands by the eighth month (Saga, 2002). The human body has 2 - 4 million sweat glands, of which the total number is fixed, with the majority being comprised of eccrine glands, across almost the entire surface of the human body (Baker, 2019). Whereas apocrine and apoeccrine glands are limited to specific regions of the body and, therefore, have a smaller role in the volume of sweat production (Harker, 2013).

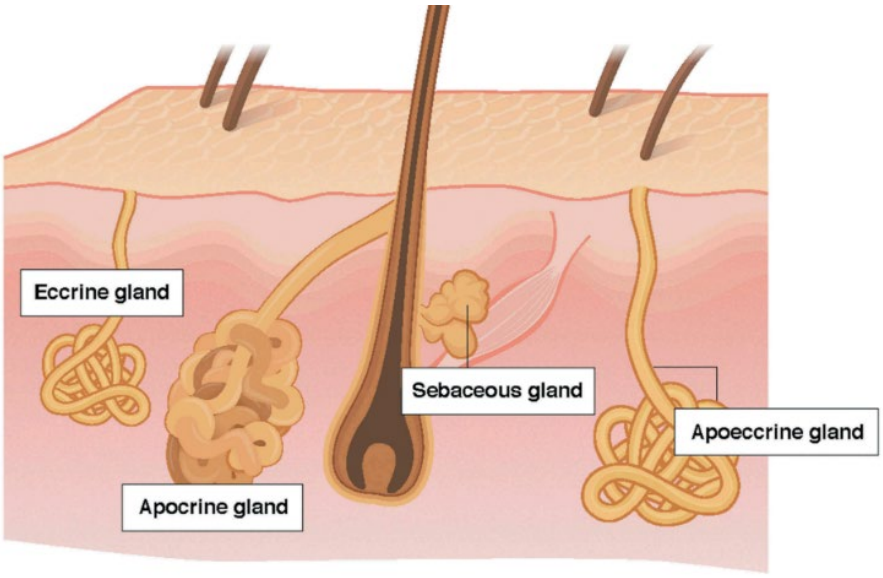

Figure 5. Schematic of apocrine, eccrine and apoeccrine glands in the axilla (Baker, 2019) © copyright [2019], reprinted by permission of Informa UK Limited, trading as Taylor & Francis Group.

2.2.2.1.1 Eccrine Sweat Gland

As mentioned above, eccrine sweat glands can be found over most of the human body, with two exceptions, the lips and glans penis, with an average density of 200 sweat glands per square centimetre. Each gland is innervated by multiple nerve fibres and a dense network of capillaries and serves as the most effective thermoregulatory function, via evaporative heat loss due to the direct secretion of sweat onto the surface of the skin (Hodge et al., 2018, Gagnon and Crandall, 2018). The composition of eccrine sweat varies based on health, exercise and hydration, but

consists of 99% water and electrolytes (Morgan et al., 2004, Saga, 2002, Mitsubayashi et al., 1994).

2.2.2.1.2 Apocrine Sweat Gland

In contrast to the above, the apocrine glands are larger in size and are based solely in hairy regions of the body, such as the axilla, genital region, breast, scalp and ear canals, as they open and secrete into the hair canal, rather than the skin surface (Wilke et al., 2007). Although these glands exist at birth, they do not become active with secretion until puberty (Schmidt-Rose et al., 2013). Apocrine glands produce a viscous, odourless and lipid-rich substance comprised of proteins, sugars and steroids (Baker, 2019, Wilke et al., 2009). These sweat glands respond to emotional stimuli such as stress, anxiety, or sexual arousal (Shelley et al., 1953).

2.2.2.1.3 Apoeccrine Sweat Gland

Unlike the other two sweat glands, this is a hybrid gland that develops from the eccrine sweat gland between the ages of 8 -14 years, making up a total of 45 % of the axillary glands by the age 16 - 18 years (Sato et al., 1987). This understanding has been presumed based on the proportion of eccrine glands decreasing with age (Wilke et al., 2007). As the name suggests, apoeccrine glands share properties with both eccrine and apocrine glands, yet are intermediate in size and limited in distribution, confined to the axillary region only. Similar to eccrine glands, apoeccrine glands secrete copious volumes of saltwater fluids onto the surface of the skin from the distal duct (Sato et al., 1987). The innervation and specific role of the apoeccrine glands are still unknown, but due to the inefficiency of evaporation at the underarm, it is unlikely to play a pivotal role in thermoregulation (Baker, 2019).

2.2.2.1.4 Thermoregulatory Sweating

It has been widely recognised that the main physiological mechanism of sweating is to dissipate heat, thereby regulating body temperature. Thermoregulatory sweating is carried out by the vastly distributed eccrine sweat glands over the body to facilitate cooling via evaporation. Thermosensitive neurons detect changes in core body temperature, triggering a sudomotor response (Saga, 2002). The sweat gland activation via the sudomotor response is controlled by the integration of numerous afferent signals from central and peripheral thermoreceptors, resulting in increased skin sympathetic activity and efferent neural signals for sweat production

(Gagnon and Crandall, 2018). Vasodilation of the blood vessels increases blood supply to the skin's surface to carry fluid from the microvascular vessels into the eccrine sweat ducts, where the water particles diffuse onto the surface of the skin and evaporate, further enhanced through increased skin temperature (Parsons, 2007). In the early 70s, it was established that sweating is controlled through the integration of both skin and core temperature, whereas previously, it was thought that core temperature alone was the driver (Nadel et al., 1971). Yet, the increase in core temperature is nine times more effective in stimulating sweat response than an increase in mean skin temperature (Nadel et al., 1971). Thermoregulatory sweating is affected by sex, fitness level, circadian rhythms and menstrual cycle (Kaciuba-Uscilko and Grucza, 2001).

The presence of sweat on the skin was first described as a physical variable of skin wetness by Gagge (1937), and is defined as the fraction of the body covered by liquid at skin temperature (e.g., sweat) involved in the process of evaporation. Further research established that increases in skin wetness are associated with corresponding increases in perceived thermal discomfort (see 2.3) (Gagge et al., 1967). This may provide evidence, particularly relevant for APDO applications, as the residual fluid post skin-product contact may increase thermal discomfort during lingering 'wet-feel', but the extent to which skin-moisture interactions for associated wetness perception during and post-stimulus contact is yet to be investigated.

2.2.2.1.5 Psychological Sweating

Another mechanism of sweat production is through psychological stress, also known as emotional sweating, which can be triggered as a response to excitement, fear, stress, anxiety and pain (Shelley and Hurley, 1953). Unlike thermoregulatory sweating, emotional sweating occurs independently of temperature and decreases through parasympathetic activation during relaxation and sleep (Wilke et al., 2007).

Psychological sweating in the axilla is problematic due to the enclosed skin site, where sweat cannot readily evaporate, and in turn accumulates, becoming noticeable by themselves and others (Swaile et al., 2012). Societal beliefs perceive excessive sweating and malodour as offensive, and as a consequence, reduce a person's self-confidence (Schmidt-Rose et al., 2013). This can result in a cycle of; increased anxiety leading to sweating, sweat secretion leading to self-awareness of sweat, and malodour, which in turn, can lead to further increases in anxiety, resulting in more sweating (Harker, 2013). The build-up of sweat as a physical presence of wetness on the underarm skin can lead to thermal discomfort (Fukazawa and Havenith, 2009, Gagge et al., 1967) and triggers the conscious behaviour of applying an APDO product (section 2.1).

2.2.2.2 Hair Follicles

The dermis contains hair follicles in 90 % of the body, which is known as hairy skin. Glabrous (non-hairy) skin is located in the palms, soles, lips and genitalia. The size, shape and density of the hair follicle vary among body regions (Vestita et al., 2022). The hair follicle is a complex epithelial structure, with three types: Lanugo hair, which sheds soon after birth, Vellus hair, which is fine and distributed mostly over the body, and Terminal hair, which is longer and coarse (Lai-Cheong and McGrath, 2021, Buffoli et al., 2014). The axilla is classified as a hairy skin site with terminal hair, although individuals remove their underarm hair as part of a hygiene routine.

From a receptor standpoint, the abundance of hair follicles are innervated by subdermal, myelinated, fast-conducting Aβ and Aδ fibres, slowly adapting type I and type II receptors, and rapidly adapting receptors, which respond to external mechanical stimuli, including sweat running across the skin and/or hair deflection during contact with external stimuli (e.g. application of APDO) (McGlone et al., 2014, Moore et al., 2025, Ackerley et al., 2014b).

Previous research has highlighted differences in wetness perception between hairy (i.e. non-glabrous) and glabrous skin regions of the body; yet it is unclear how local wetness perception differs at the same body region, such as the underarm, in the presence and absence (i.e. shaven) of hairs. Ackerley et al. (2012) reported no differences in wetness sensitivity between hairy and glabrous skin sites in females when assessed using a single dynamic stroke. In contrast, Filingeri et al. (2014b) provided preliminary evidence of differences in wetness perception between hairy and glabrous skin sites in males during the application of cold-wet, neutral-wet, and warm-wet stimuli. These stimuli were applied either statically (providing only thermal cues) or dynamically (providing both thermal and tactile cues). Their findings indicated a trend for greater wetness perception with cold-wet stimuli across both skin sites, with perceived wetness increasing significantly during dynamic compared with static application. Overall, the hairy skin site showed greater wetness sensitivity than the glabrous skin site.

Differences between these studies may partly reflect the sex of participants, as thermal sensitivity has been reported to differ between males and females, with females generally demonstrating greater thermal sensitivity, which contrasts with these findings. However, methodological differences in stimulus application are also likely to explain the contrasting findings. In the study by Ackerley et al. (2012) stimuli were applied using a single dynamic stroke across the skin, and saturated the cotton patch with a maximum of 0.08 ml of water. Whereas, in Filingeri et al. (2014b) study participants moved their limb across the probe twice in an up–down motion and saturated the cotton patch with 2 ml of water. Humans can discriminate wetness differences as small as 0.02 ml (Sweeney and Branson, 1990), with a minimum detection threshold of approximately 0.04 ml (Tiest et al., 2012), and greater moisture volumes

are associated with increased perceived wetness (Filingeri and Havenith, 2015). Consequently, the larger moisture volume used in Filingeri et al. (2014b) study likely resulted in greater wetness detection regardless of the stimulation site.

Importantly, both studies investigated the forearm as the hairy skin region, which contains fine vellus hair. To date, no studies have examined static and dynamic applications for wetness perception at a terminal hair site such as the underarm. Furthermore, previous work has primarily compared hairy and glabrous skin sites rather than examining the same anatomical site with hair present versus removed. This highlights a key gap in understanding how the biophysical properties of the skin, including the presence and removal of hair, may influence wetness perception at the underarm.

2.2.2.3 Sensory Receptors

The skin contains a range of specialised sensory receptors that transduce mechanical, thermal, and nociceptive stimuli into neural signals. Cutaneous receptor populations are highly heterogeneous across the body, differing in receptor type, density, receptive field size, and functional specialisation according to the sensory demands of each skin site (Corniani and Saal, 2020). However, the exact density and distribution of these receptors remain difficult to quantify due to methodological limitations, including challenges in extrapolating findings between glabrous and hairy skin with differing tactile fibre compositions (Corniani and Saal, 2020).

Cutaneous receptors relevant to wetness perception primarily include Aβ mechanoreceptive afferents and Aδ thermoreceptive afferents. Mechanoreceptors are classified according to their response to skin stimulation as either fast-adapting (FA), responding to dynamic motion, or slow-adapting (SA), responding to sustained deformation or stretch. These can be further subdivided into type I afferents, located superficially within the skin, and type II afferents, located deeper within the dermis (Corniani and Saal, 2020). The four principal mechanoreceptive afferents include Meissner corpuscles (FAI), Pacinian corpuscles (FAII), Merkel cell complexes (SAI), and Ruffini endings (SAII), which contribute to the perception of pressure, vibration, stretch, and texture (Macefield, 2005, Ackerley et al., 2014a). Hairy skin (2.2.2.2) additionally contains hair follicle and field afferents, primarily classified as FAI units. Importantly, the density and distribution of these receptive fields vary considerably across body regions; for example, the digits possess substantially greater densities of Meissner corpuscles and Merkel cells than the palm (Corniani and Saal, 2020).

In addition, free nerve endings function primarily as thermoreceptors and nociceptors. Thermoreceptive afferents detect changes in skin temperature and include both cold- and warm-sensitive fibres. Cold-sensitive Aδ fibres are rapidly conducting and play a fundamental role in detecting temporal decreases in skin temperature, contributing significantly to wetness perception (see 2.4.1.1) through the integration of thermal and mechanical inputs (Filingeri et al., 2014a, Schepers and Ringkamp, 2009). In contrast, C fibres are slow conducting thermoreceptive afferents responsive to both cooling and warming stimuli (Corniani and Saal, 2020, Olausson et al., 2024).

Consequently, although similar receptor classes are distributed throughout the skin, their functional output and resulting sensory perception may vary across body regions due to differences in receptor organisation, innervation density, and local skin properties. A regional body-mapping study demonstrated that the axilla exhibits thermal and wetness sensitivity comparable to other body sites. However, sensitivity varied according to stimulus type and sex, with females demonstrating approximately 14–17% greater sensitivity to cold-wet stimuli than males (Valenza et al., 2019). The authors noted that gentle shaving of the underarm prior to testing may have altered direct stimulus contact in males, potentially reducing sensation. Furthermore, only the central axillary region was assessed, limiting generalisation across the axilla despite known regional differences in biophysical properties (i.e. SCH and epidermal thickness) across the centre and periphery. Therefore, research lacks a site-specific regional understanding of sensory perception experienced at the underarm during external stimuli contact, and how intra-biophysical variations may alter this perception.

Given the axilla's role in sweating, there are direct links to thermal comfort, behavioural thermoregulation, and the crucial role of thermal sensing for wetness detection, which will be detailed in the section below.

2.3 Thermal Comfort

Amongst the mechanisms that maintain thermal homeostasis, the subjective experience of thermal comfort plays a central role in how individuals perceive and evaluate their environment. Thermal comfort is defined as a state of being that expresses satisfaction with the thermal environment (Flouris, 2019, Nagashima et al., 2018). Unlike thermal sensation, which reflects the neural processing of afferent inputs from peripheral and central thermoreceptors in response to a given stimulus (American Society of Heating and Engineers, 1997). Thermal comfort reflects the subjective experience of a thermal stimulus, rather than the sensory

detection of temperature itself, influencing behavioural responses (i.e. removing clothing when feeling too warm) (Parsons, 2007). When core temperature remains stable, change in skin temperature is the primary determinant of comfort, highlighting the importance of cutaneous thermosensory input in shaping subjective experience (Marks and Gonzalez, 1977).

Perception of skin wetness—whether from sweat accumulation or external moisture skin contact—is strongly associated with increased thermal discomfort and plays an important role in behavioural thermoregulation (Kerslake, 1972, Schlader et al., 2010). Wetness-related comfort varies across body regions, with areas such as the head and torso contributing differently to overall comfort (Fukazawa and Havenith, 2009), likely due in part to spatial differences in thermosensitivity and summation of thermal inputs. However, the underarm is a region that is yet to be investigated.

Thermal comfort cannot be explained solely by peripheral receptor distribution. Thermal signals from the skin and core are integrated centrally, including processing within the insular cortex, where they are transformed into conscious experiences of comfort or discomfort (Nakamura and Morrison, 2008). Thermal comfort is therefore determined by a comparison between the perceived thermal state and an internally defined “desired” state. When perceived wetness—largely inferred from cooling-driven changes in skin temperature—exceeds this comfort threshold, discomfort arises, and behavioural responses are initiated. While responses may include pacing activity or adjusting clothing, this framework is particularly relevant to the underarm. Excessive perceived wetness in this region, even in the absence of large sweat volumes, may reduce local comfort and motivate the use of APDO as a targeted behavioural strategy to reduce perceived wetness and restore comfort. However, the initial wet contact and evaporative cooling associated with APDO application may decrease local thermal comfort, despite the product being used as a behavioural response intended to improve subsequent comfort. In addition, users may actively expect a thermal change during application; for example, spray or roll-on formulations often produce a cooling sensation that aligns with user expectations and perceived product efficacy. In contrast, gels or sticks are typically applied at room temperature and are therefore more thermo-neutral. Understanding the mechanisms underlying wetness perception on the skin could help inform product development aimed at improving thermal comfort during APDO application.

2.3.1 Thermal Sensation

Thermal sensation, particularly skin cooling, is fundamental to wetness perception, given the absence of dedicated hygroreceptors in the skin. Wetness is therefore inferred largely from

thermal cues, meaning that principles governing temperature sensation are central to understanding how moisture is perceived during external stimuli contact, such as during APDO application. Four key factors influence thermal sensation: absolute skin temperature, rate of temperature change, stimulus size, and body region.

Absolute skin temperature determines sensitivity to thermal stimuli. Within a neutral range (~30 – 34 °C), there is little or no thermal sensation perceived (Hensel, 1981). If baseline temperature lies outside this range, thresholds for detecting warm or cold sensation shifts requiring a greater skin temperature change to elicit sensation (Hensel, 1981). Thus, the initial baseline skin temperature influences how intense a stimulus, such as the moisture-skin interaction during external stimuli contact, will be perceived.

The rate of change in skin temperature is particularly important for thermal sensation and wetness detection. A faster rate of skin cooling during external stimuli contact produces a greater thermal sensation and lowers perceptual threshold, whereas slower changes require larger temperature shifts to be detected (Kenshalo et al., 1968). This is representative of a real-life scenario where the skin contacts an external stimulus and is exposed to skin warming or cooling, for example, during APDO application, the rapid heat exchange between the product and the skin may induce transient cooling, amplifying both thermal sensation and perceived wetness.

With regard to the stimulus area, it is known that the size of the area being stimulated on the skin impacts the temperature sensation. An increased area of the skin exposed to either warm or cold stimuli lowers the temperature threshold to induce a thermal sensation (Hensel, 1981). This is based on the understanding of the spatial summation of thermally sensitive receptors in the skin (Kenshalo et al., 1967). If the area of the skin has a high density of receptors, then less of the skin needs to be stimulated for a thermal sensation (Filingeri, 2016). Therefore, the skin surface area contacted by an external stimulus may influence the magnitude of cooling and thus, wetness perceptions. Furthermore, temperature spatial gradients may also influence thermal sensitivity (Krænge et al., 2026). When a small, localised area of skin is cooled while surrounding regions remain thermally neutral, the contrast between the cooled and neutral areas may increase the perceptual intensity of the cooling stimulus, potentially strengthening the perceived sensation of cold (Krænge et al., 2026) and, consequently, wetness.

The region of the body being stimulated impacts the thermal sensitivity experienced. It has long been known that there are regional differences, which impact both physical and perceptual experiences (Hensel, 1981). Regional differences in the distribution of warm- and cold-sensitive receptors mean that the same thermal stimuli can be perceived differently across the body. For example, a higher density of cold-sensitive receptors in the torso compared with the head may

result in greater sensitivity to cooling in that region. These regional differences are particularly relevant to the underarm, where thermal sensitivity remains underexplored. Understanding how the underarm responds to temperature stimuli is essential for optimising APDO formulations, as the initial thermal interaction between product and skin may shape perceived wetness, comfort, and overall product experience.

Taken together, these principles of thermal sensitivity provide the physiological foundation for understanding wetness perception. Factors such as baseline skin temperature, rate of cooling, stimulus size, and regional sensitivity determine the magnitude of thermal afferent signalling, which in turn shapes both the intensity of perceived cooling and the likelihood that a stimulus will be interpreted as “wet.” This is particularly relevant at the underarm, where product application and changes in the skin's biophysical properties interact. Building on this thermal sensation framework, the following section will explore the mechanisms underpinning wetness perception and how these contribute to thermal comfort and APDO product application experience.

2.4 Wetness Perception

2.4.1 Background

Over the past four decades, it has been understood that the human skin lacks the presence of hygroreceptors, a type of humidity sensor that specialises in wetness detection (Clark and Edholm, 1985). These receptors have been identified in other species in the animal kingdom, such as fruit flies (Enjin et al., 2016) and stick insects (Tichy, 1987), allowing certain animals the ability to respond to small changes in ambient humidity for survival (Merrick and Filingeri, 2019, Filingeri, 2015). Despite the lack of hygroreceptors in the human skin, wet stimuli such as rain running across the skin can still be detected. The synthetic perception of wetness has been described as a ‘learnt’ sensory experience, through skin contact with a wet fluid or when sweat is produced (Filingeri and Havenith, 2015). Sensing humidity and skin wetness has been shown repeatedly to impact thermal comfort and, thus, is critical for behavioural thermoregulation and survival (Gagge, 1937, Filingeri and Havenith, 2018). For example, as mentioned (see 2.3), a behavioural response to wet thermal discomfort at the underarm would be applying an APDO product.

To our knowledge, Bentley was the first scientist to investigate this perception through his famous ‘synthetic experiment’ in the 1900s. It was hypothesised that the sensory-blending

phenomenon, a combination of pressure and temperature, enhanced with coldness, could evoke the perception of wetness (Bentley, 1900). During the series of tests, participants were blinded, whilst their finger was submerged in beakers of various liquids, and their sensations were assessed. In one case, a thin rubber sheath was placed over the finger, which functioned as an interface between the finger and the liquid. Despite no physical contact with the liquids, participants perceived wetness, refusing to believe that the finger was not wet (Bentley, 1900). Here, the novel psychological experience of wetness perception was highlighted.

Scientific research in wetness perception has continued, identifying that skin wetness, whether during contact with an external wet stimulus (Filingeri et al., 2014b), or the internal activation of sweat gland production during exercise (Filingeri et al., 2015c), relies on the interaction of the somatosensory system (Figure 6). Integrated thermal sensitive receptors in our skin detect the presence of moisture through evaporative changes in skin temperature via heat exchange. The reduction in skin temperature creates a cold sensation. Through learnt experiences, this coldness could be perceived as wetness. Furthermore, mechanosensitive receptors in the skin detect static and dynamic movement and pressure, whilst wet stimuli are on the skin, this could aid in detecting wetness. Our perception of wetness is shaped by our previous sensory experiences during the interaction of thermal and mechanical cues, occurring on the surface of the skin when wet (Filingeri and Havenith, 2015).

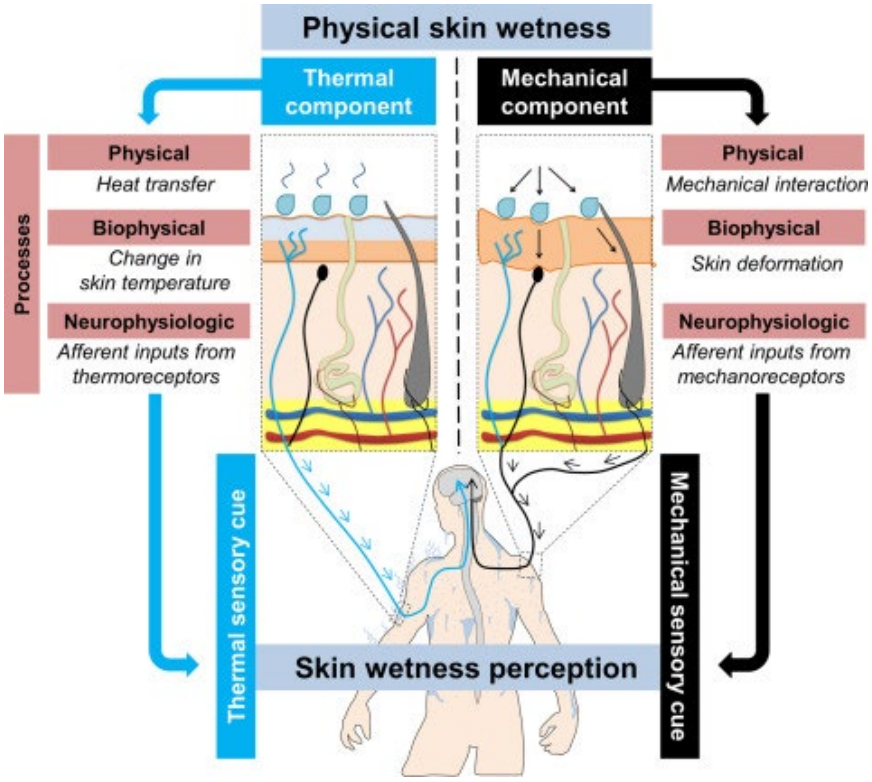

Figure 6. Mechanisms identified (thermal and mechanical inputs that convey sensory information) for the integration of human skin wetness perception, in the absence of skin hygroreceptors (Filingeri and Havenith, 2015) © copyright [2015], reprinted by permission of Informa UK Limited, trading as Taylor & Francis Group.

2.4.1.1 Multisensory Integration

Small changes in skin temperature evoke warm or cold sensations via temperature-sensitive primary afferents in both hairy and glabrous skin (Schepers and Ringkamp, 2009). Cold perception is primarily mediated by myelinated Aδ fibres, which respond maximally between ~20 – 30 °C and conduct rapidly, whereas warmth is mainly encoded by slowly conducting unmyelinated C fibres, which increase firing at higher temperatures (Schepers and Ringkamp, 2009, McGlone and Spence, 2010). These afferent signals are centrally integrated and ascend via higher-order neurons through the spinothalamic tract to the thalamus and primary somatosensory cortex, where temperature is consciously perceived, creating the experience of wetness (Figure 7) (Kandel et al., 2000, Filingeri, 2016).

At the molecular level, Transient Receptor Potential (TRP) ion channels are thought to underpin peripheral thermal sensation. TRPM8 mediates cold detection (activated < 26 °C) and has been

involved in wetness perception, while TRPV3/4 are associated with warmth (Tominaga and Caterina, 2004, Typolt and Filingeri, 2020). Because humans lack hygroreceptors, wetness perception is thought to rely heavily on cold-sensitive Aδ input driven by skin cooling (Filingeri and Havenith, 2015). Indeed, dry-cold stimuli can also evoke wetness sensations, whereas warm- or neutral-wet stimuli suppress them, demonstrating the significance of thermal cues (Filingeri et al., 2014b, Filingeri et al., 2015d).

Alongside thermal inputs, tactile cues play a key role in wetness perception (Bentley, 1900, Tiest et al., 2012, Filingeri et al., 2015c). Mechanical information ascends via the dorsal column–medial lemniscus pathway to the somatosensory cortex, where tactile sensations are consciously processed (Figure 7) (Ackerley and Kavounoudias, 2015). Manipulating mechanical stimuli such as movement or friction can alter perceived wetness independently of actual moisture levels (Filingeri and Ackerley, 2017, Merrick et al., 2022b). Wetness can therefore be experienced during sweat–fabric interaction (Filingeri et al., 2015c) or haptic exploration of wet materials (Bergmann Tiest, 2015). Notably, dynamic movement of even neutral-temperature wet stimuli can elicit wetness perception, indicating that mechanical interaction alone may be sufficient under limited thermal cues (Ackerley et al., 2012, Filingeri and Ackerley, 2017).

Low-threshold mechanoreceptors mediate these tactile signals. In glabrous skin, Meissner corpuscles, Merkel discs, Pacinian corpuscles and Ruffini endings detect touch, pressure, vibration and skin stretch, while hairy skin contains Merkel, Pacinian and Ruffini afferents (Ackerley and Kavounoudias, 2015). The majority of wetness research has applied a temperature-modulated wet stimulus to the skin of various glabrous and vellus hairy regions, which are fine hairs distributed mostly over the body (see 2.2.2.2), with limited investigation of terminal hairy regions, which are longer and coarser, such as the underarm (Lai-Cheong and McGrath, 2021, Buffoli et al., 2014).

Hairy (vellus) and glabrous skin differ anatomically and physiologically in ways that may influence wetness perception. Hairy skin is generally more thermally sensitive, whereas glabrous skin has greater tactile spatial acuity due to a higher density of Merkel cells, yet has a thicker stratum corneum, which reduces thermosensitivity (Norrsell et al., 1999, Rushmer et al., 1966). Therefore, as cooling plays a central role in wetness perception, hairy skin may be more sensitive to wetness, however, there is conflicting evidence (see 2.2.2.2). Furthermore, even less is understood about the integration of mechanoreceptors and wetness detection in terminal hairy skin.

The optimal stimulus for wetness sensing likely occurs when cold moisture contacts and moves across the skin, simultaneously activating thermal and tactile afferents (Filingeri and Ackerley, 2017), like during contact with an APDO fluid during application. However, this multisensory

integration requires further investigation into the mechanism of wetness perception in a region as unique as the underarm.

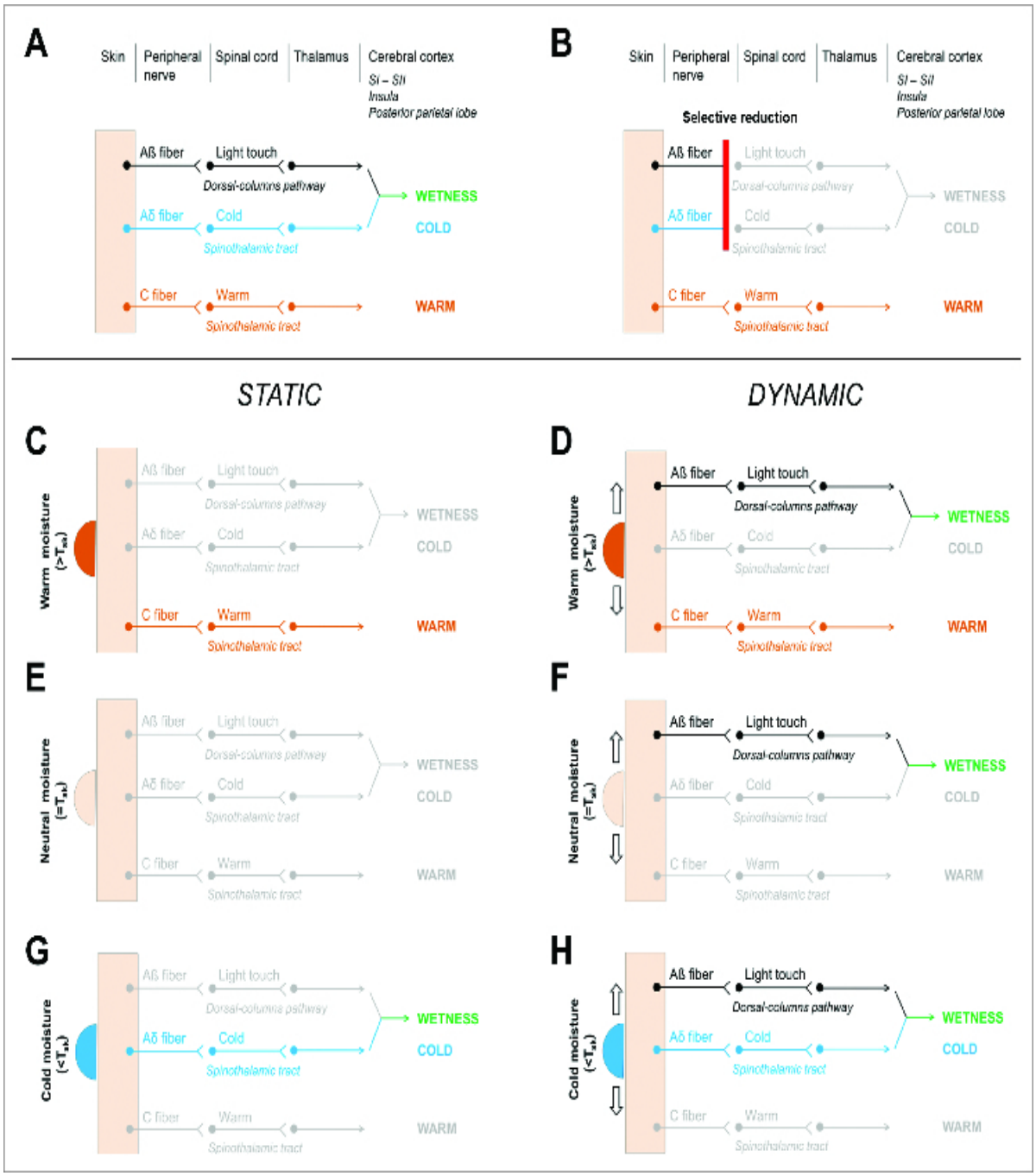

Figure 7. Neurophysiological model of cutaneous wetness sensitivity, specific to thermal and tactile sensory cues (Filingeri and Havenith, 2015) © copyright [2015], reprinted by permission of Informa UK Limited, trading as Taylor & Francis Group.

2.4.2 Anatomical Skin Site

Human wetness perception has traditionally been investigated across several anatomical sites, most commonly the forearm, fingertip, torso, back, neck, forehead and foot (Ackerley et al., 2012, Buoite Stella et al., 2022, Merrick et al., 2021, Valenza et al., 2019, Wildgoose et al., 2021, Christogianni et al., 2022). Across these regions, evidence consistently supports the mechanism identified in the multisensory integration wetness perception model (see 2.4.1.1), i.e. in the absence of dedicated hygroreceptors, wetness arises from the integration of thermosensory (cooling-driven) and mechanosensory (movement-driven) inputs (Filingeri et al., 2014b). There have been consistent observations across body regions that cold-wet stimuli are experienced as wetter (Filingeri, 2014), than neutral-wet and warm-wet (Filingeri et al., 2014a). Regional differences in cold-wet sensitivity have been mapped, with increased sensitivity following a cranio-caudal pattern (i.e. the foot was more sensitive than the head) (Valenza et al., 2019). Available evidence suggests that the study by Valenza et al. (2019), is currently the only one that has directly investigated wetness perception at the underarm, which highlighted similarities with previous research in wetness response to the different temperature stimuli (i.e. cold-wet feeling wetter), with a greater sensitivity to cold-wet stimuli for females compared to males (see 2.2.2.3). The author concluded that the difference in thermal and thus wetness sensitivity could be driven by body morphology, which is an important factor of spatial summation in thermosensing; as such, a greater proportion of their skin was being stimulated by the fixed-size thermal probe for the females.

Yet, the unique biophysical characteristics of the underarm were not considered in the study, highlighting the need for further investigation of wetness perception at the underarm for greater understanding of inter-and-intra site specific differences (section 2.2.1). This gap is notable given the unique biophysical characteristics of the axilla, including terminal hair, variations in epidermal thickness within the region and frequent fluctuations of the stratum corneum from shaving and APDO use. Alterations in SCH and barrier properties have been shown to modulate thermal and tactile sensitivity (section 2.2), suggesting that hair density and hydration state may influence afferent signalling and thus, wetness perception at this site. However, the extent to which these anatomical and biophysical features modify wetness processing at the underarm remains unknown.

2.4.3 Type of Stimuli

Most wetness studies have applied external stimuli to the skin for magnitude estimation testing (see 3.2), typically involving ~10 s contact with a temperature-controlled probe (~2 – 25 cm^2)

varying in temperature (-2 to -20 °C below skin temperature) (Filingeri et al., 2013b), with a wetted cotton patch (moisture: 0 and 50 ml) (Merrick et al., 2021), and applied either statically or dynamically (Raccuglia et al., 2018, Merrick et al., 2022a). It has been established that cold-wet stimuli during static application are consistently perceived as wetter than warm- or neutral-wet stimuli at equivalent moisture contents (Jay and Havenith, 2004, Valenza et al., 2023). Indeed, static cold-dry stimuli have shown to evoke wetness perception when skin cooling occurs at a specific rate (0.14 to 0.41 °C.s^{-1}), demonstrating the role of thermal cues (Filingeri et al., 2013b). Furthermore, when the external wet stimuli are applied dynamically, tactile cues are stimulated and aid in the perception of wetness, specifically when the thermal cues are limited (i.e. neutral, 30 °C or above skin temperature, 35 °C) (Tiest et al., 2012, Filingeri et al., 2014b). Collectively, these studies have investigated the effect of the single-component fluid of water during external application, which provides little research into how fluids with varying thermal properties, specifically thermal conductivity and heat capacity, like those in APDO products, may influence the perception of skin wetness (see 2.1.2). Material discrimination studies have highlighted the importance of a higher thermal conductivity and heat capacity in the identification of a material, due to greater total skin cooling during contact (Jones and Berris, 2003, Ho, 2018). Furthermore, Bergmann Tiest (2015) recognised that the haptic exploration for wetness discrimination of wet materials, varying in thermal properties, was influenced by transient heat transfer during skin-material contact. Whilst wetness perception is known to rely on skin cooling, greater perceptions have been experienced with greater rates of skin cooling (Filingeri et al., 2013b). This could imply that fluids with higher thermal properties might elicit a greater wetness through an increased magnitude of skin cooling during contact. Nevertheless, this is yet to be investigated. Also, given that combining fluids alters their thermal properties, and that APDO comprise mixtures of components with differing conductivities and heat capacities (Kazemi et al., 2025), the wetness response to such blends—particularly at the underarm—has never been explored, leaving substantial gaps regarding how real-world product formulations feel upon application.

2.4.4 Wetness Assessment

Quantitative sensory testing (QST, see 3.2) of wetness has predominantly relied on the validated, single time-point assessment on a visual analogue scale (VAS), obtained during brief (~10 s) contact (Valenza et al., 2025). While this approach has been influential in defining the understanding of the “acute” wetness mechanisms, it provides limited insight into its temporal development, including and not limited to how wetness emerges at contact onset, changes during stimulation lasting beyond ~10 seconds, and the decay in wetness perception after

stimulus removal. Current approaches that typically rely on the single time-point scale do not reflect the time-dependent changes in perception (i.e. from dry to very wet and from very wet back to dry) that characterise real-world skin–moisture interactions. For example, applying an APDO product to the underarm will likely produce a sequence of perceptual phases: initial wetness upon contact, a progressive increase in perceived wetness, a plateau of perception for repeated application and a gradual decline once contact ends. Capturing only the start of these moments (i.e. likely the initial contact) risks overlooking the depths of the temporally changing perception. This contrasts with pain research, where continuous psychophysical methods are routinely used to track perceptual curves (Burge and Bonnen, 2025, Schestatsky et al., 2007, Medici et al., 2013). Pain research using continuous assessment methods has demonstrated characteristics within pain sensation, such as pain onset, maximum pain, and decline of pain after maximum sensation (Schestatsky et al., 2007, Medici et al., 2013, Campolo et al., 2022), highlighting the need for a high-resolution continuous scale to identify whether similar key characteristics can be identified during stimuli contact for wetness perception. Similar to the activation of nociceptors for pain perception, wetness requires the activation of thermal afferents for detection (Arens and Zhang, 2006). Thermoreceptor responses are inherently dynamic; as such, cold-sensitive Aδ fibres exhibit rapid, phasic firing at stimulus onset followed by adaptation during sustained stimulation (Spray, 1986, Hensel, 1981, Campolo et al., 2022). These time-dependent changes in peripheral firing translate into evolving central perceptions, as demonstrated in nociceptive research where stimulus intensity and duration shape perceived magnitude over time (Spray, 1986, Medici et al., 2013). By comparison, wetness perception is likely to reflect not only the magnitude of skin cooling but also the rate of temperature change and subsequent receptor adaptation, resulting in distinct perceptual phases during and after contact. Without continuous assessment, these informative components of wetness remain poorly understood.

2.5 Summary of Literature Review

- **Antiperspirant deodorants** reduce sweat and odour, yet product acceptability depends heavily on sensory experience during application. Reformulation pressure (e.g., removal of volatile silicones) raises concerns that altered fluid thermal properties (thermal conductivity and heat capacity) may increase cooling and perceived wetness, but the role of application-induced wetness at the underarm remains unclear.

- **The axilla** is a biophysically distinct, hairy, warm and humid site with dense eccrine, apocrine and apoeccrine glands, variable epidermal thickness, and fluctuating SCH influenced by shaving and APDO product use. Hair follicles and SCH may modify mechanical and thermal signalling, yet intra-axillary regional differences of wetness perception are largely unexplored.

- **Thermal comfort** depends primarily on skin temperature changes when core temperature is stable, and regional differences in thermosensitivity influence comfort responses. Skin wetness, whether from sweat or external moisture skin contact, is strongly linked to thermal discomfort and behavioural thermoregulation. However, the contribution of underarm wetness to local thermal comfort, from exposure to a wet stimulus, remains underinvestigated.

- **Wetness perception** arises from multisensory integration of cooling-driven thermoreceptor input and mechanoreceptor activation, due to the lack of hygroreceptors. Most research uses short (~10 s), water-based, single time-point assessments at non-axillary sites, demonstrating that greater skin cooling increases perceived wetness. Key gaps include limited study of the underarm, unknown effects of modulated biophysical skin properties such as hair and SCH, lack of research on fluids with varied or blended thermal properties (in APDO), and poor understanding of the time-course of wetness perception beyond initial contact.

2.6 Knowledge Gaps

After reviewing and summarising the literature, key knowledge gaps have been identified, and some fundamental research questions have been established in line with the industry partners' motivations, which focus on understanding wetness perception during external stimuli application to transfer this knowledge to the real-world scenario of applying an APDO. Therefore, the first observation and knowledge gap refers to the mechanisms for wetness perception as site-specific regional differences are yet to be established at the underarm, despite being a unique region of the human body which interacts with external moisture throughout the day, whether during the application of an APDO or during hygiene routines (i.e. showering). Which would be relevant from an applied standpoint for the understanding of wetness perception during initial contact with an APDO product, which can be used to improve thermal comfort upon application.

Additionally, many individuals partake in a personal care routine such as shaving the underarm, therefore the area undergoes changes in the biophysical properties of the skin, such as the presence of hair or SCH, yet the role of hair or hydration on the wetness perception experienced during external wet stimuli contact is yet to be investigated. This is relevant for the industry partner as consumers may be applying an APDO among a range of these scenarios; therefore, understanding and informing product design and consumer satisfaction.

Finally, the research on wetness perception has typically focused on the application of short-duration (~10 s) contact with a wet (i.e. water) external stimulus. So, it is unknown whether wetness perception would be experienced differently during the application of a range of fluids. Furthermore, a method to assess the temporal development and decay in wetness perception is yet to be established. This would be relevant for P&G to gain an insight into the impact their fluid formulations might have on wetness perception and the time-dependent changes for a full picture during the application process (i.e. wetness perception upon initial contact with the underarm, during extended contact [> 10 s], and upon product removal).

Therefore, relevant research questions have been listed below:

- Do the mechanisms that underpin wetness perception at other regions of the body align with the underarm's response? (Chapter 4).
- How does the biophysical status of the underarm skin impact sensitivity to wetness perception, such as fluctuation in SCH? (Chapter 4 and 8).
- How does the presence and removal of hair at the underarm impact wetness perception during static and dynamic external stimuli application? (Chapter 5).
- Does wetness perception change temporally if an external stimulus is applied to the underarm for prolonged contact (> 10 s), and is this wetness profile influenced by the fluid applied? (Chapter 6 - 8).
- Given the role of cooling cues in wetness detection and in material discrimination research, how will the interaction of single and blended fluids (in APDO) with varying thermal properties impact the rate of change in skin temperature and, subsequently, wetness perception? (Chapter 6 - 8).

2.7 Aims and Objectives

The overall goal of this PhD was to evaluate wetness perception at the underarm using external stimuli to investigate the role of skin biophysical and fluid thermal properties. The applied implications of this research are to inform APDO design for product application, with support from P&G, a global consumer goods manufacturer and full funder of this PhD.

Considering the literature review and areas for research development, the specific aims and objectives of the PhD are as follows:

1. **Determine the mechanisms for wetness perception at the underarm during static external stimulus application and the role of stratum corneum hydration on wetness perception (Chapter 4).**

   Objectives

   - Recruit healthy volunteers varying in sex and ethnicity to ensure the protocol's practicality for differences in the underarm's anatomical morphology,
   - Examine the feasibility of applying the established single time-point QST to the underarm,
   - Develop a method to manipulate the biophysical state, such as the hydration status of the skin at the underarm, outside the range of baseline values,
   - Measure a range of non-invasive anatomical, perceptual, and biophysical variables to quantify changes in skin sensitivity to cold-wet, neutral-wet and warm-wet stimuli.

2. **Evaluate the role of hairiness on wetness perception during static and dynamic cold-wet stimuli application to the underarm (Chapter 5).**

   Objectives

   - Develop a method to apply a stimulus dynamically on the skin in a scientifically controlled manner,
   - Recruit male healthy volunteers who do not frequently remove their underarm hair to investigate differences in hairy vs shaven biophysical conditions on wetness perception response,
   - Collect a variety of perceptual parameters to explore the role of hair for wetness and thermal sensitivity during static and dynamic stimulus application.

3. **Explore a new quantitative sensory testing method to assess temporal changes in wetness perception with a range of external stimuli at the forearm (Chapter 6).**

   Objectives

   - Develop a continuous VAS to assess changes in wetness perception during extended (> 10 s) probe contact,
   - Model the dynamic relationship between skin temperature and wetness perception whilst a cold-wet stimulus is applied to the skin, by extracting parameters such as peak wetness perception and magnitude of skin cooling using a bespoke MATLAB code,
   - Identify key trends and phases in the wetness perception curve and quantify the relevant parameters for data analysis,
   - Detect if the new method is sensitive enough to discriminate between fluids varying in their thermal conductivity and heat capacity properties,
   - Establish the reliability and set minimum detectable change thresholds for the extracted parameters.

4. **Establish the role of a single fluid's thermal properties on skin cooling and consequently skin wetness perception during and after contact with a cold-wet stimulus at the underarm (Chapter 7).**

   Objectives

   - Deploy the newly developed QST to the underarm,
   - Build on and refine the data analysis from Chapter 6 and identify key wetness perception parameters to depict differences and similarities between fluids during and after stimulus contact,
   - Model the temporal change in skin temperature during and after stimulus contact and identify key phases of the cooling curve,
   - Identify if the thermal conductivity and heat capacity of the fluid applied impact skin cooling rates and thus, influence wetness perception response.

5. **Investigate the effect of the blended fluid combination and the role of skin hydration on wetness perception at the underarm (Chapter 8).**

Objectives

- Combine two known fluids to create a new blended mixture for investigation using the continuous wetness perception assessment,
- Establish the effect of combined fluid thermal properties on skin cooling and wetness perception,
- Design a method to overhydrate the skin to replicate a real-world scenario of a shower,
- Ensure the protocol for overhydration provides a SCH increase above 20 % from baseline,
- Examine the effect of the fluids on wetness perception whilst the skin is overhydrated, to identify the role of skin hydration on fluid behaviour.

Chapter 3 Methodology

This chapter provides an overview of methodologies and measurements used in this PhD Thesis to assess skin wetness perception at the underarm during the application of external stimuli resembling APDO product application.

Table 1 provides a summary of methods and outcome measures across all experimental chapters. The overarching methodological approach to assess wetness perception in this Thesis consisted of:

1) The design and execution of bespoke QST, which allowed the delivery of controlled temperature and wetness stimuli to the underarm, under varying biophysical states (e.g. hydration and hairiness).
2) The concurrent measurement of skin biophysical responses to such stimuli during and following application (e.g. changes in skin hydration and temperature).
3) The evaluation of the resulting subjective perceptions of wetness (alongside touch and temperature, where appropriate).

The following sections will discuss in detail each of the three areas above, highlighting the advantages and limitations of each method employed.

Table 1. Summary of methods and outcome measures across the experimental chapters.

Study Chapter	Methods/Methodology	Outcome measures
Chapter 4	Stimuli delivery: • Quantitative sensory testing • Overhydration/dehydration protocol Biophysical assessments: • Infrared thermography • Tympanic thermometry • Skin capacitance measurements (Corneometer) • Optical coherence tomography Perceptual evaluation: • Visual analogue scale • Von Frey monofilaments	Stimuli delivery: • Magnitude estimation • Changes in stratum corneum hydration Biophysical assessments: • Local skin temperature • Estimated core temperature • Stratum corneum hydration • Epidermal thickness and surface roughness Perceptual evaluation: • Wetness perception and thermal sensation • Tactile threshold estimation

Chapter 5	Stimuli delivery: • Quantitative sensory testing • Hairiness/ removal of hair Biophysical assessments: • Infrared thermography • Tympanic thermometry Perceptual evaluation: • Visual analogue scale	Stimuli delivery: • Magnitude estimation • Changes in skin biophysics Biophysical assessments: • Local skin temperature • Estimated core temperature Perceptual evaluation: • Wetness perception and thermal sensation
Chapters 6 and 7	Stimuli delivery: • Continuous quantitative sensory testing • Fluid thermal properties Biophysical assessments: • Infrared thermography • Thermocouple • Tympanic thermometry • Skin capacitance measurements (Corneometer) Perceptual evaluation: • Visual analogue scale	Stimuli delivery: • Magnitude estimation • Changes in the rate of skin cooling Biophysical assessments: • Local skin temperature- spot measure • Local skin temperature- temporal measure • Estimated core temperature • Stratum corneum hydration Perceptual evaluation: • Wetness perception
Chapter 8	Stimuli delivery: • Continuous quantitative sensory testing • Fluid thermal properties • Overhydration protocol Biophysical assessments: • Infrared thermography • Thermocouple • Tympanic thermometry • Skin capacitance measurements (Corneometer) Perceptual evaluation: • Visual analogue scale	Stimuli delivery: • Magnitude estimation • Changes in the rate of skin cooling • Changes in stratum corneum hydration Biophysical assessments: • Local skin temperature- spot measure • Local skin temperature- temporal measure • Estimated core temperature • Stratum corneum hydration Perceptual evaluation: • Wetness perception

3.1 Ethics

The laboratory methods undertaken are described in the experimental protocols within each of the experimental chapters and were approved by The University of Southampton's Ethical Committee (Appendix A).

ERGO 73017:

- The effects of stimulus temperature and skin hydration on wetness perception at the underarm (Chapter 4).
- The impact of hair on local skin wetness perception at the underarm during static and dynamic applications of cold-wet stimuli (Chapter 5).

ERGO 81776:

- A novel high-resolution methodology to assess temporal changes in skin wetness perception during and following wet stimuli contact (Chapter 6).
- Time-dependent changes in skin wetness perception at the underarm during contact with fluids varying in thermal properties (Chapter 7).
- Time- and hydration-dependent changes in skin wetness perception at the underarm during contact with individual and blended fluids varying in thermal properties (Chapter 8).

Equipment set-up and testing procedures were completed in accordance with the Declaration of Helsinki. Following familiarisation with a participant information sheet, the testing procedures and laboratory equipment, participants signed an informed consent form. A health screen questionnaire was completed by every participant to ensure suitability for each specific study (criteria below), to ensure safety, improve study reliability, and reduce confounding factors that may influence the results.

Inclusion criteria:

- Male or Female;
- 18 - 40 years old;
- Regularly shaving/waxing/trimming underarm hairs;
- Regularly use antiperspirant deodorants;
- Physically active (i.e. performing regular exercise 1 to 3 times a week);

Exclusion criteria:

- Overweight (BMI > 30);
- Family history of cardiovascular diseases;
- Suffering from cardiovascular, metabolic, or neurological disorders;
- Neuro-diverse participants with diagnosed attention disorders (e.g. Autism)
- Suffering from skin conditions (e.g. eczema);
- Presence of conditions altering thermoregulation and blood flow (e.g. Raynaud's disease);

- Taking prescribed medications for a health condition associated with cardiovascular, metabolic, or neurological disorders;
- Known allergy to water, mineral oil, propylene glycol, dimethicone and polyethylene glycol;
- Smoker or Vaper;
- Pregnant, post-partum or breastfeeding.

3.2 Quantitative Sensory Testing

The experimental approach adopted in this thesis is grounded in traditional psychophysics, which seeks to quantify the functional interaction between controlled physical stimuli and subjective perceptual responses. By methodically manipulating stimulus properties, such as temperature, volume, and contact duration, and measuring corresponding changes in reported sensation, psychophysics enables the construction of a stimulus–response paradigm that characterises perceptual sensitivity (Gescheider, 2013). Within this framework, perception is conceptualised according to a Bayesian multisensory integration model of sensory processing, whereby subjective experience reflects the probable integration of incoming sensory evidence with prior experience (Deneve and Pouget, 2004). In the context of wetness perception, afferent thermal and tactile signals during skin–fluid interaction contribute to the sensory likelihood, while learned associations between skin cooling and moisture contact act as priors, generating a perceptual experience. Integrating QST with a Bayesian framework provides both methodological and theoretical foundations, allowing controlled stimulus delivery and measurement of perceptual response in a standardised laboratory setting.

QST is a psychophysical method used to assess the functions of the sensory neuron pathways by applying controlled, standardised stimuli to a region of the body and recording a participant's subjective response, such as wetness perception, thermal sensation and pain (Chong and Cros, 2004). In a research context, QST provide a controlled way to investigate how peripheral receptors (i.e. thermoreceptors, mechanoreceptors, and nociceptors) contribute to perceptual experiences (Chong and Cros, 2004), and can generate outcomes such as detection thresholds, which determine the minimum stimulus intensity to detect a sensation (i.e. dichotomous choice) and magnitude estimation, which quantifies the perceived intensity of a stimulus above threshold (i.e. VAS). A major strength of QST is its reproducibility, as stimulus intensity, duration and temperature are tightly controlled. It is non-invasive and widely transferable between experimental contexts (Rolke et al., 2006). However, QST relies heavily on subjective reporting, making outcomes vulnerable to influences such as expectations, prior experience, and

attention (Yarnitsky, 1997). Despite these limitations, it remains a valuable tool for quantifying sensory perception under controlled conditions.

To decipher the correct QST methodology to assess wetness perception for the specific study aims, a systematic approach may be used (Merrick et al., 2022a). Firstly, the source of moisture will be determined as either internal (i.e. sweat production) or external (i.e. wet stimulus contact) for the wetness assessment. Then the testing framework to assess the perceptual responses to the moisture source, such as detection threshold (i.e. force-choice) or magnitude estimation (i.e. ratio scales, Figure 8), will be selected. This process will ensure essential differentiation of specific skin-moisture scenarios and ensure the resulting thermo-tactile inputs can be correctly assessed. This initial framework evaluation will provide suitable experimental methods to assess wetness perception for the investigational outcomes (Merrick et al., 2022a).

Detection thresholds typically rely on the dichotomous choice method, which is also referred to as a forced choice, where participants must decide between stimulus options, for example, ‘Does this material feel wet?’ Y / N. In some cases, a staircase method is used, where stimulus moisture volume or temperature will ascend or descend depending on the response to the initial stimulus. This provides good region comparisons and high sensitivity, however, stimulus repetition is needed, therefore, the cognitive and sensory fatigue could set in, reducing the reliability of the results (Swets, 1961). Whereas, magnitude estimation tests are likely used for perceptions, such as wetness, due to their ease of use and adaptability (Merrick et al., 2022a). This test approach typically requires someone to report their perception of a presented stimulus, likely on a VAS by marking a point between the labelled descriptors (i.e. 0 mm = dry, 100 mm = extremely wet, Figure 17). This method can capture intensity differences between stimuli, binary outcomes such as wetness perception and thermal sensation, and has high sensitivity. However, this has a high cognitive load, training is required before use, and it has a high level of variability (Fukuda et al., 2021).

In wetness perception studies, QST method for magnitude estimation has been measured using a single time-point VAS (see 2.4.4), to mitigate some of these limitations, evidence from continuous psychophysics will be utilised to develop a continuous VAS for time-dependent changes in wetness perception response (see 3.4.1) for its ecological validity and a richer informative dataset (Campolo et al., 2022, Medici et al., 2013, Burge and Bonnen, 2025). However, both options rely heavily on the user's familiarity to ensure they understand the anchor points and what they relate to, ensuring full use of the scale rather than an individual subconsciously favouring an area of the scale, reducing resolution (Merrick, 2022).

Overall, the most appropriate QST chosen for the studies in this PhD is the magnitude estimation technique with VAS. With appropriate scale design and participant familiarisation, this approach enables the quick and easy collection of high-resolution magnitude estimation data with strong consistency between conditions.

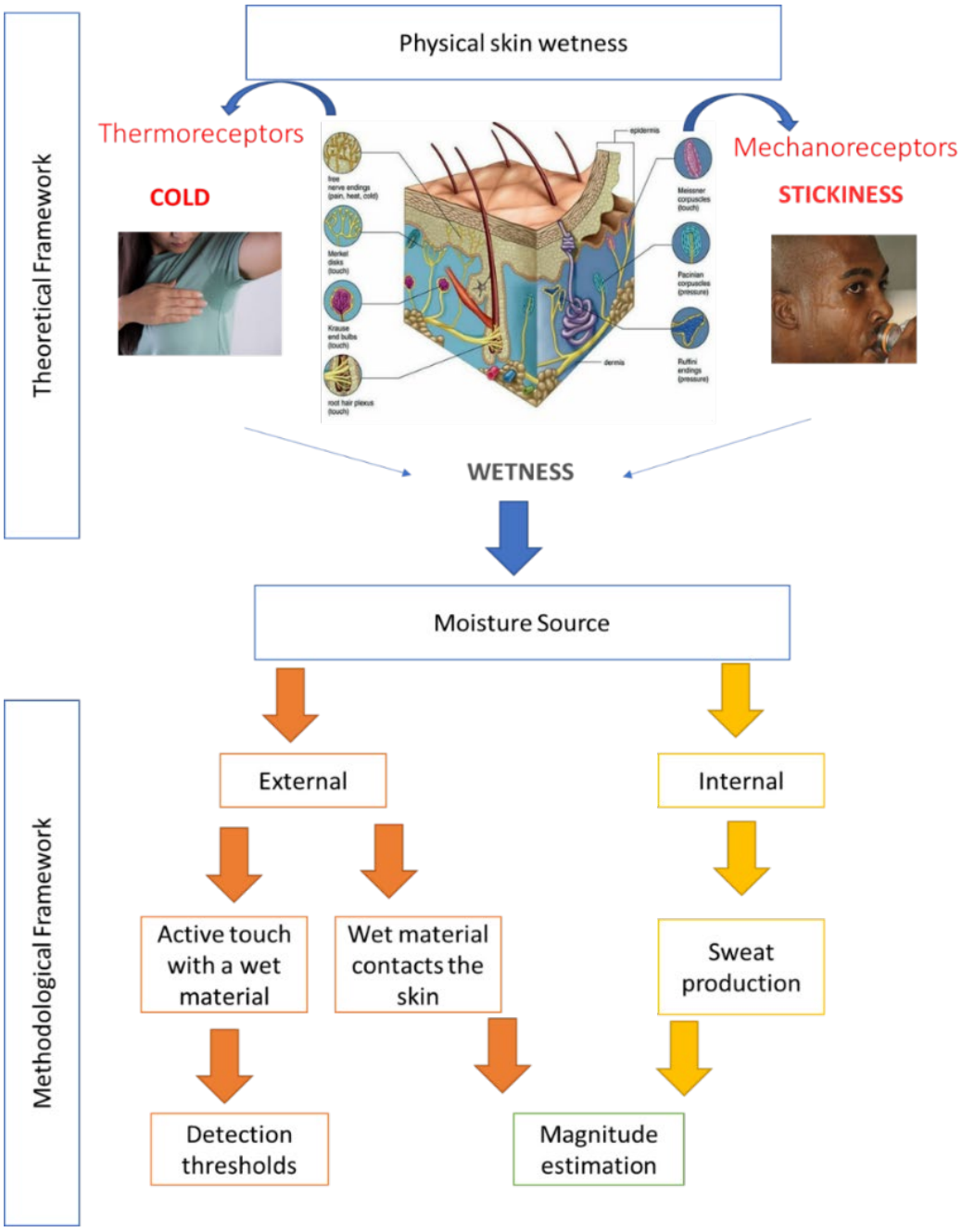

Figure 8. Methodological framework for measuring wetness perception. Reprinted with permission and adapted from (Merrick et al., 2022a).

3.2.1 Temperature-Controlled Probe

For magnitude estimations of wetness perception, a temperature-controlled probe is required to deliver external stimuli to a region of the skin. The system comprises of the stimulator (thermal probe; Physitemp Instruments Inc., USA), a control unit to which the probe, driven by a thermoelectric (Peltier) model, is connected, a pump, and a tank unit (Figure 9A). The control unit has a baseline adjustment range of 20 - 30 °C using three dials (± 5 °C, ± 1 °C and ± 0.1 ° C), with a response time in heating and cooling of < 4 s of the thermal probe. According to the manufacturer's description, the device's temperature could be controlled to a ± 0.1 °C resolution, meaning highly controlled precision during measurement. However, when investigating the reported validity, the device failed to meet the claims (Versey et al., 2011).

The stimulator was equipped with interchangeable probes of two geometries: a circular probe (1.32 cm^2) and a larger square probe (25 cm^2, Figure 9B). This allowed optimisation of skin–probe contact according to the anatomical region and experimental objective. Probe size was selected carefully, as the area of stimulation directly influences thermosensory perception due to spatial summation of activated thermally sensitive receptors (see 2.3.1). Regions with higher receptor density require smaller stimulation areas to evoke equivalent perceptual responses, whereas larger areas may amplify thermal sensation through greater afferent recruitment. Subsequently, probe selection was incorporated into the study design to control for these effects. In Studies 1 and 2 (Chapter 4 and Chapter 5), the smaller circular probe was used to target discrete underarm subregions while preventing stimulation overlap that could confound sensory activation and perceptual reporting. In contrast, Study 3 - 5 (Chapter 6 - 8) employed the larger square probe to stimulate a broader axillary area, enabling assessment of local skin cooling under full-contact conditions that more closely replicate APDO product application.

Additionally, for the requirements of prior experimental trials, a built-in integrated load cell to measure force during application was incorporated in the square probe. This modification has made the equipment bespoke, as such exact resolution for this is unknown and therefore should be considered when using the force measurements during application. As the small probe does not have an integrated load cell, the standardised protocol for ensuring adequate and consistent force during probe application is to ensure full contact without visible and pronounced skin indentation. Although it is noted that this is not as accurate in recording force during application.

In this context, the strengths of using the thermal probe outweighed its limitations. Therefore, to assess wetness perception, a cotton patch was secured to the top of the thermal stimulator using an elastic band (Figure 9C). The cotton patch was saturated with various room

temperature (~23 °C) fluids using a volume pipettor and applied to the underarm region at a force of < 1 N.

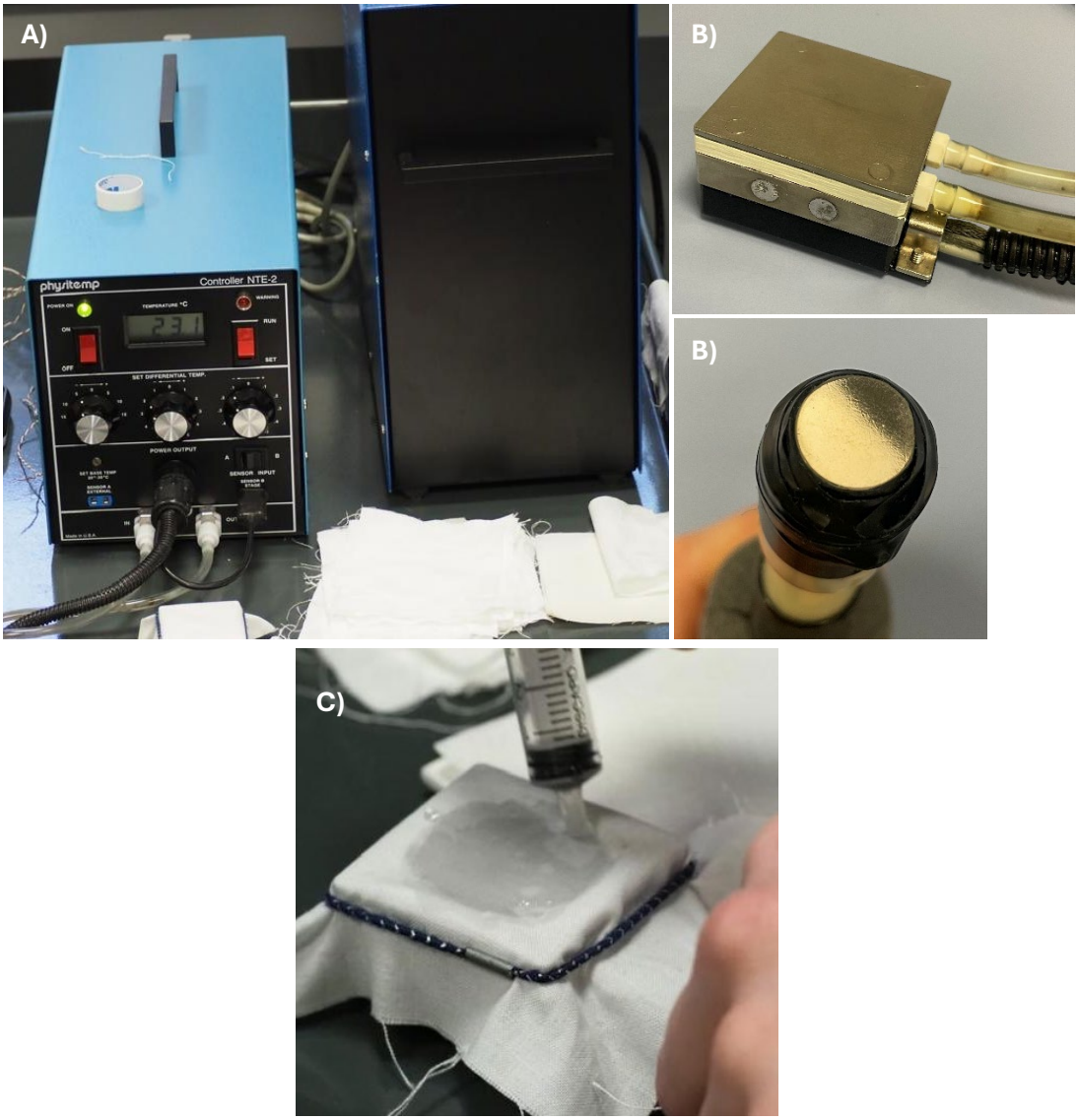

Figure 9. A) Temperature-controlled thermal probe unit (Physitemp). B) The different-sized thermal probes: the large square probe and the small circle probe. C) The testing setup of the temperature-modulated probe and wet cotton patch secured on top before being applied to the skin.

3.2.2 Fluid Thermal Properties

The various room temperature (~23 °C) fluids saturated on a cotton patch and secured onto the thermal probe and applied to the underarm varied in their thermal properties. The two main fluid thermal properties that were focused on were thermal conductivity and heat capacity (see 2.1.2). Thermal conductivity can be described as the material's ability to conduct heat and

therefore influences the rate at which thermal energy is transferred between fluid and skin during contact. Heat capacity is defined as the amount of thermal energy required to raise the temperature of a fluid by one degree, which determines the fluid's ability to absorb or release heat. These thermal properties could influence and shape the magnitude and temporal profile of skin cooling and thus, wetness perception.

The fluids selected for the experimental Chapter 6 - 8 were carefully considered for variations in thermal characteristics (Table 2), yet similar in other properties such as non-toxic, colourless, and odourless, and they were all applied randomly at the same temperature (i.e. 23 °C), and in the same volume (1 mL) to ensure discrimination from biophysical and perceptual responses rather than application bias.

The raw fluids and their specific thermal conductivity and heat capacity values were provided by a chemical formulations research fellow at P&G for their relevance in ADPO formulation and design. The selected fluids were water, propylene glycol (PG), mineral oil (MO), dimethicone (PMX), polyethylene glycol (PEG), and 50/50 water/PEG (blend) (Figure 10). It must be noted that the fluids range in other physical properties, such as viscosity, density and surface tension, such as PEG has a higher viscosity than water, which could impact tactile inputs when in contact with the skin, and thus wetness perception. This should be considered when observing differences in wetness response with fluid application, yet the greatest influence is likely thermal conductivity and heat capacity for APDO application, which is why they were the focus when determining the fluids.

Table 2. Fluid's thermal conductivity and heat capacity, and which experimental chapters they are used in.

Fluid	Chapter	Thermal conductivity (W/m·K)	Heat capacity (J/g·C)
Water	4, 5, 6, 7 and 8	0.598	4.18
PG	6 and 7	0.206	2.49
PMX	6 and 7	0.153	1.52
MO	6 and 7	0.136	1.67
PEG	8	0.194	2.24
Blend	8	0.337	3.42

Note: PG = propylene glycol, MO = mineral oil, PMX = dimethicone, PEG = polyethylene glycol and Blend = 50/50 water/PEG.

Figure 10. Raw fluid (water, polyethylene glycol, and 50/50 water/polyethylene glycol experimental set-up for testing protocol.

3.3 Biophysical Assessments

3.3.1 Skin Temperature

3.3.1.1 Thermocouple

Skin temperature was measured using two methods across the experimental studies. For temporal changes with skin-probe interactions, a thin T-type thermocouple (RS Components Ltd, Coby, UK) was placed on the surface of the skin in the centre of the testing site (forearm; the midpoint between wrist and antecubital fossa and underarm; over the midaxillary line, 10 cm above the nipple line) and secured with tape, with the sensor tip touching the skin and exposed, i.e., not covered by tape (Figure 11). This was connected to a data acquisition board and software to collate concurrent measurements of temperature upon skin stimulation. The thermocouple consists of two small wires welded into a smooth bead (0.25 mm) that exchanges heat with the skin and substrate through several microscopic contact points (Rykaczewski and Dhanote, 2022) and can measure temperatures in a range of -200 to 200 °C with high sensitivity and stability (Yang et al., 2011). They have been observed to be able to detect small changes in temperature with a sensitivity as high as 20.6 μV/°C with a response time below 2 s, and a sampling frequency of 10 Hz (Sheng et al., 2022).

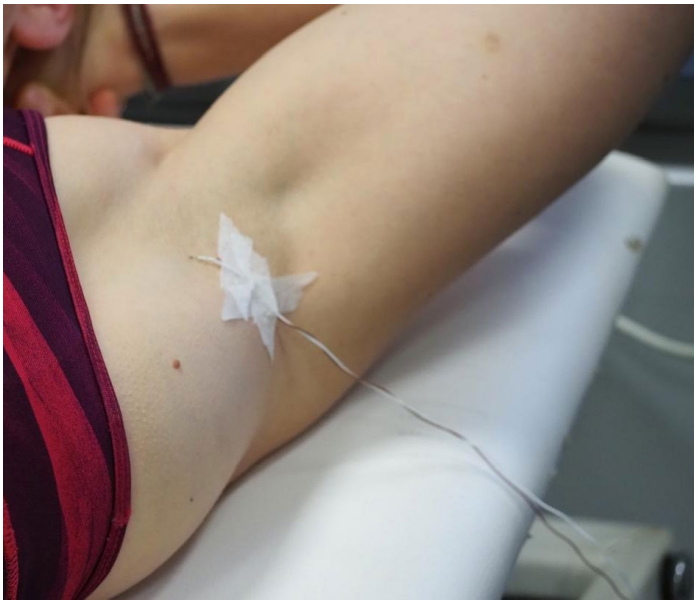

Figure 11. T- type thermocouple (RS Components), which measures temporal changes in local skin temperature.

Thermocouples were incorporated to monitor probe–patch interface temperature, providing an objective indicator of skin–probe contact consistency at the testing site. This was particularly important given potential spatial variability in contact arising from inter-individual differences in the anatomical contour of the axillary fossa. Variations in surface curvature may influence local heat transfer and, consequently, perceptual outcomes. To address this, during piloting of the continuous wetness perception test (c-WPT; see 3.4.1) and in Study 3 (Chapter 6), five additional thermocouples were affixed to the probe surface, with the cotton patch secured over them (Figure 12). This configuration enabled spatially distributed temperature monitoring to ensure stable and uniform contact throughout stimulation.

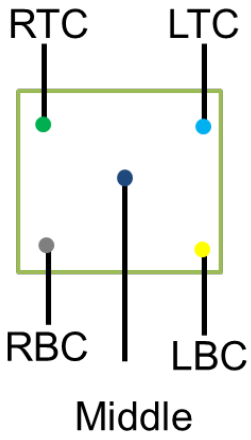

Figure 12. Schematic of the setup for the thermocouples on the surface of the probe to identify the spatial difference in temperature change at the underarm. *RTC = right top corner, LTC = left top corner, RBC = right bottom corner, and LBC = left bottom corner.*

3.3.1.2 Infrared

In addition to the local continuous skin temperature measure, a single-spot infrared thermometer (Spot IR Thermometer TG54; FLIR Systems, Wilsonville, OR, USA) was used for relative changes in local skin temperature at rest, before and after applying the external thermal probe. Infrared thermography provides a non-contact, non-invasive method for efficiently obtaining skin temperature through thermal radiation detection from the skin's surface (Nikkhah, 2014), and are suitably accurate when assessing skin temperature changes under resting conditions similar to those of the QST (James et al., 2014). The device is handheld and provides a colour palette to display the temperature (range of -20 to 659 °C) of an object, making it user-friendly and descriptive (Figure 13). On the other hand, these devices are expensive on initial purchase, which requires specialised software, and measurements cannot be taken at the interface between the skin and the thermal probe.

The effectiveness of infrared thermography provides sufficient advantages to offset the disadvantages required for two different purposes in the current studies. For Studies 1 and 2 (Chapter 4 and Chapter 5), the measurement was used to identify the local skin temperature change before and after thermal probe application, and to determine the set point for the external thermal probe temperature before applications (i.e., 5 °C above local skin temperature). For Studies 3 - 6 (Chapter 6, Chapter 7, Chapter 8) the infrared camera was used as a rapid spot check measure of the local skin temperature between repeated stimulus applications to ensure the area being stimulated had rewarmed to baseline temperature before

the next application. Finally, it was used to ensure that once saturated with the fluid, the thermal probe and cotton patch had equalised to the set unit temperature (23 °C) before application.

Figure 13. Handheld infrared thermography camera for thermal imagery of local skin temperature.

3.3.2 Skin Hydration

SCH was assessed using a rapid (~1 s), non-invasive capacitance measurement obtained via a Corneometer (CM 825, CK Electronics, Germany; Figure 14). The probe is placed directly on the skin surface, where controlled spring displacement (optimal depth: 10 – 20 µm) enables electromagnetic measurement of surface capacitance according to a standardised protocol. Readings are expressed in arbitrary units (AU), reflecting relative rather than absolute water content; higher stratum corneum water content increases capacitance and produces higher AU values. A minimum of three consecutive measurements was obtained and averaged to enhance reliability (Westermann et al., 2020, Anthonissen et al., 2015). The Corneometer demonstrates a broad hydration measurement range (~120 ± 5 AU), low coefficient of variation, and strong intra-individual repeatability (Fluhr et al., 1999). It is particularly sensitive for detecting dry and very dry skin states, although sensitivity decreases at higher hydration levels (Clarys et al., 2012). Methodological limitations include the assessment of a small, single measurement area and the inability to provide continuous, real-time tracking during application. While skin temperature can influence water mobility and dielectric properties (Rossmann and

Haemmerich, 2014), evidence indicates that baseline hydration measurements are stable within normal physiological skin temperature ranges, yet temperature-dependent effects emerge with skin temperatures above ~42 °C (Morin et al., 2020), which was not reached during the present experimental protocols.

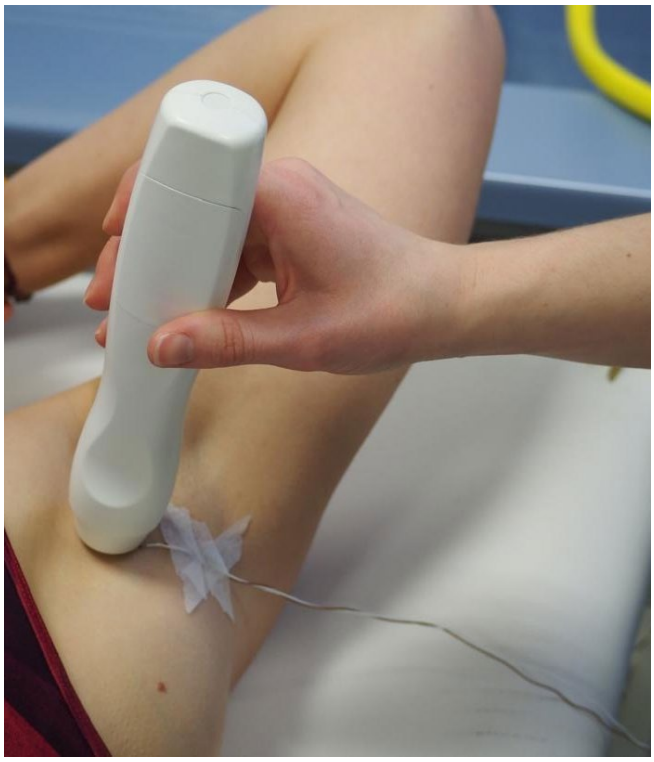

Figure 14. Corneometer (CM 825), which measures stratum corneum hydration.

3.3.3 Optical Coherence Tomography

Optical coherence tomography (OCT; Vivosight, Michelson Diagnostics Ltd, Kent, UK), is used to assess real-time skin structure and morphology using light to create a grey-value reflection profile across tissue depth (Welzel et al., 2004). OCT has a high resolution (20 - 5 µm), non-invasive and three-dimensional imaging ability (Huang et al., 2020). The development of OCT imaging speed has exceeded 300,000 A-scans/s with an operating wavelength of 680 nm to 1.8 µm (Wojtkowski, 2010). Epidermal properties such as skin surface roughness and epidermal thickness were estimated using the software associated with the imaging system (VivoTools, Michelson Diagnostics Ltd, Kent, UK). OCT imagery provides a valuable technique to generate cross-sectional images with high-resolution (Aumann et al., 2019). However, normative epidermal data for the underarm are yet to be established, which should be considered during the analysis.

3.3.3.1 Skin Surface Roughness

Skin surface roughness was derived from 2D-OCT scans as the root mean square deviation of surface peaks and troughs relative to the mean surface line (Figure 15). Using three standard numerical algorithms to produce the values Ra (the mean variation of the surface height), Rq (the root mean square variation of the surface height) and Rz (the peak-to-trough difference of the surface height at the lowest and highest points) in microns. The processing works by obtaining these 3 values along 5 lines on the surface of the skin (Maiti et al., 2020). Repeatability of measurements of skin roughness is estimated as ± 1.8 µm for Ra, ± 12 µm for Rz, and ± 2.2 µm for Rq (Kislevitz et al., 2020).

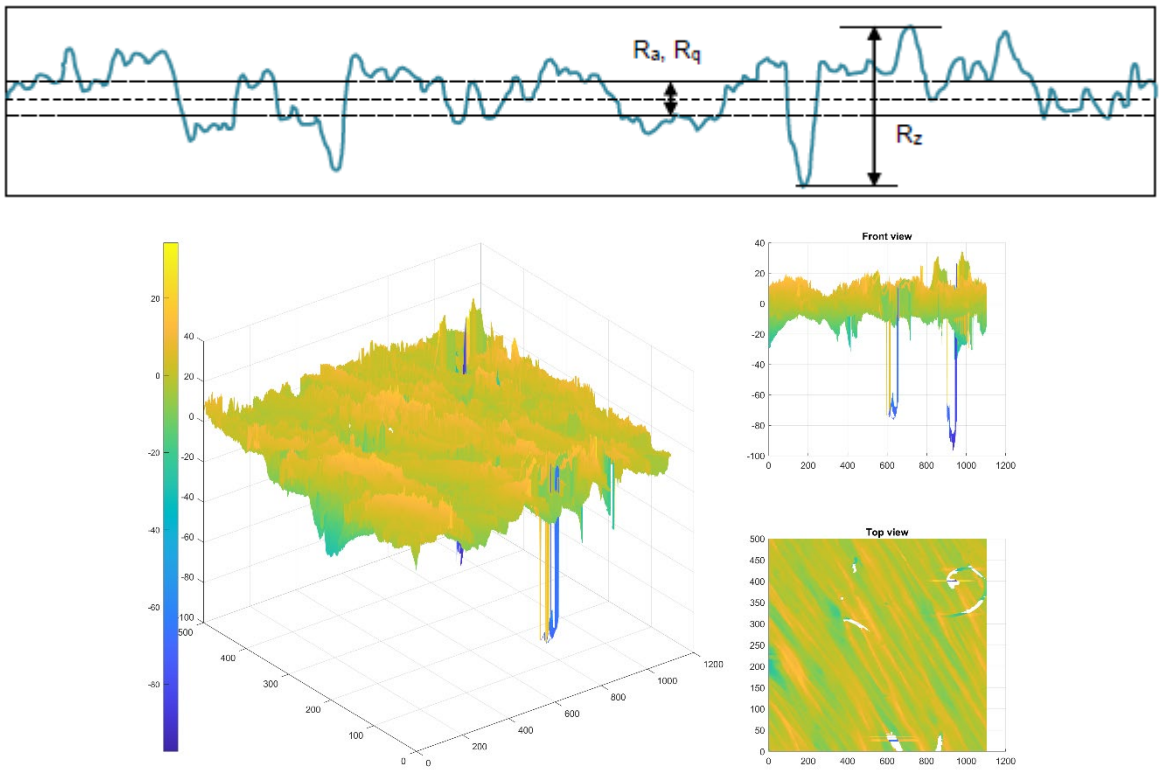

Figure 15. 2D- OCT surface roughness scan with scale of the underarm skin.

3.3.3.2 Epidermal Thickness

Epidermal thickness can be characterised by the difference in depth values between the two peaks in an average A-scan plot (Welzel et al., 2004). Peak one refers to the skin's surface, and peak two refers to the dermal-epidermal junction. The estimated repeatability is ± 10 µm, and the established variation is ± 6 µm of epidermal thickness (Kislevitz et al., 2020). Epidermal

thickness can be influenced by age, gender, skin type and anatomical location (Gambichler et al., 2006).

The A-scan obtained for the underarm lacked the second peak corresponding to the dermo-epidermal junction. This occurred because the VivoTools software identifies epidermal thickness using an automated segmentation algorithm based on the average OCT intensity profile derived from normative data. However, the specific body sites used to generate these reference profiles were not reported. The software manual also notes that this feature is not suitable for glabrous or plantar skin sites. Adabi et al. (2017) emphasised the importance of systematically analysing OCT images across different anatomical regions, as skin morphology varies considerably across the body and can influence OCT signal profiles. Consistent with this, the second peak could not be clearly detected in several underarm scans (Figure 16). To address this limitation, a customised MATLAB (MathWorks, USA) script was developed to allow manual exploration and analysis of the OCT data.

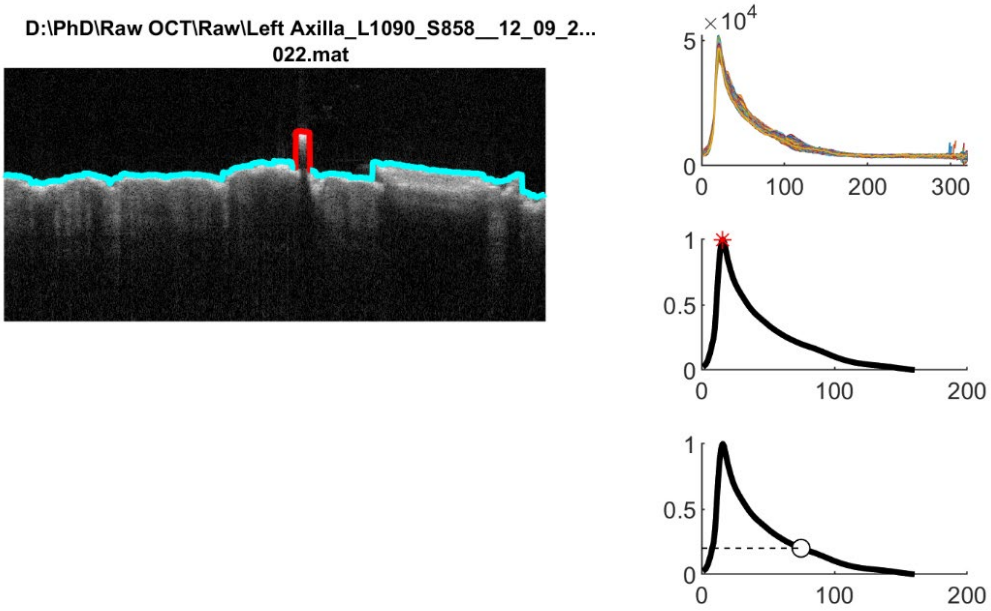

Figure 16. 2D-OCT scan of the underarm skin.

3.4 Perceptual Assessments

VAS are widely used in psychophysiological research to quantify subjective experiences such as wetness perception and thermal sensation, as they provide quick, non-invasive quantitative data that are sensitive to small perceptual changes (Gescheider, 2013, Stevens, 1957). Typically, wetness perception is presented as a 100-mm anchored scale (i.e., anchor points: 0 =

dry; 100 = extremely wet), whereas thermal sensations are presented as a 200-mm anchored scale (i.e., anchor points: 0, very cold; 100, neutral; 200, very hot, Figure 17). VAS allow participants to indicate subtle variations in intensity, improving resolution compared to Likert category scales. They have demonstrated strong reliability and responsiveness in sensory and pain research (Guyatt et al., 1987) and are particularly beneficial when displaying stimulus–response relationships or capturing suprathreshold magnitude differences. However, VAS are not without limitations: they rely on participant interpretation of anchors, may be influenced by individual scaling behaviour, which can introduce variability due to differences in response strategy. Furthermore, traditional single time-point VAS ratings do not adequately capture the temporal development of perception during sustained stimulation. These methodological considerations highlight the need for approaches that retain the sensitivity of continuous scaling while improving temporal resolution.

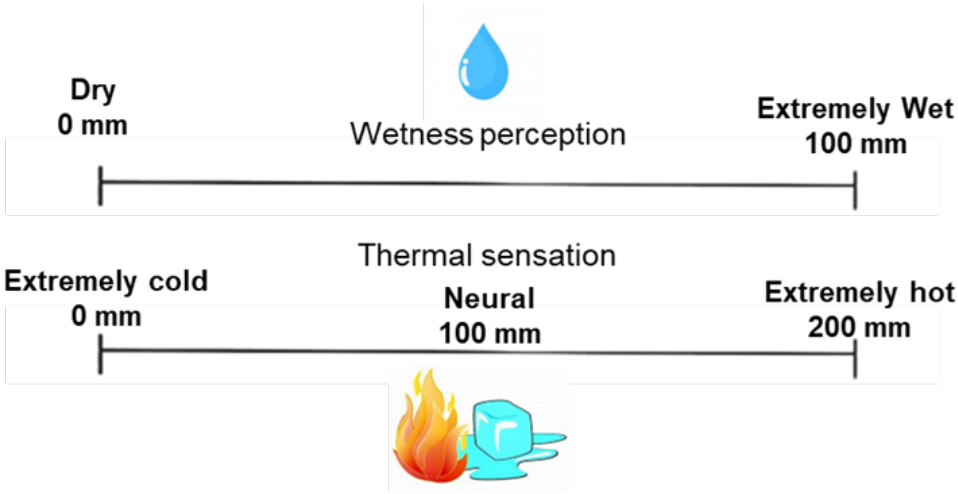

Figure 17. Visual analogue scales are used for wetness perception and thermal sensation assessments.

3.4.1 Continuous Wetness Perception Test (c-WPT) Piloting

Based on the methodological limitations of the single time-point QST, the development of the c-WPT was motivated by the need to obtain high-resolution, time-dependent magnitude estimation data capable of characterising onset, peak, and decay phases of wetness perception during realistic skin–fluid interactions like applying an APDO.

An extensive piloting phase was undertaken to understand, plan, develop, and design a new continuous QST method, known as the c-WPT, used in Chapter 6, which describes the method development and the first experimental study to implement the method to determine the

reliability and sensitivity to detect changes in wetness perception from varying contact conditions, among a cohort of healthy young females. Here, the pilot phase and digitisation of the VAS will be described.

Firstly, the length of the VAS and descriptors was kept the same (length 100 mm; 0 = dry and 100 = extremely wet, Figure 18) for consistency and reproducibility across studies, past and present. However, the scale was adapted and digitalised to be able to move the slider continuously to record the time-stamped data using the DASYLab Data Acquisition Software (MCCDAQ, Massachusetts, USA). This could be exported into Excel for descriptive analysis.

The user interface displayed a stop/start and record button to start the software and then record the data. Once these buttons had been pressed, the wetness perception scale became active, starting from 0 mm, and the integrated skin temperature was recorded. The data acquisition software was also used to collate concurrent measurements of temperature upon skin stimulation, using a thermocouple board with a T-type thermocouple (see 3.3.1.1). Data was collected with a synchronised time stamp.

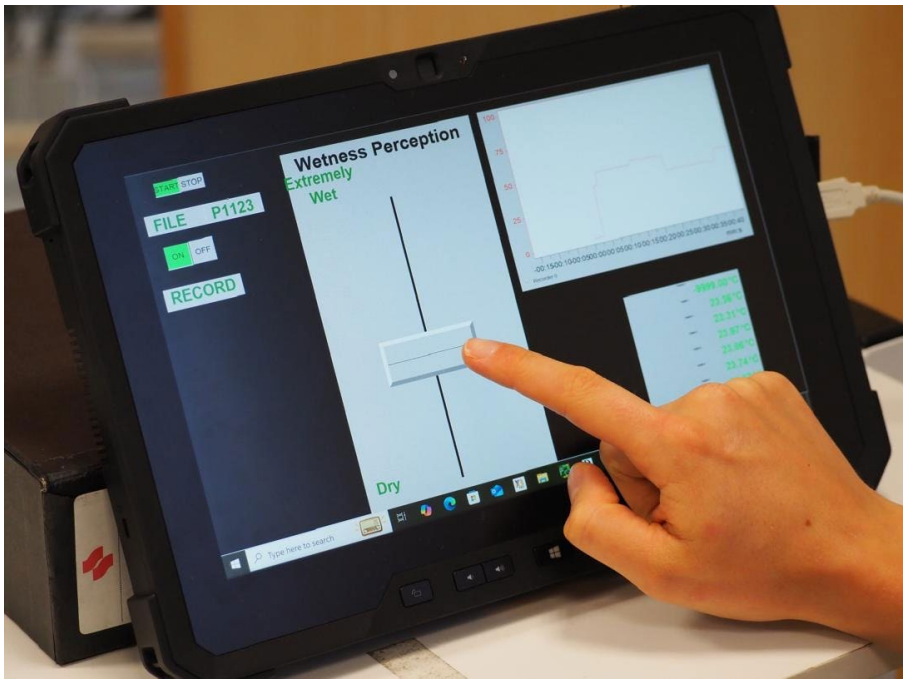

Figure 18. The visual analogue scale was developed, using the DasyLab software to continuously measure and recorded time-depended changes in wetness perception.

The c-WPT is multifaceted; therefore, piloting incorporated testing the equipment requirements to ensure valid and repeatable measures of concurrent time-driven wetness perception and skin temperature responses. Furthermore, the equipment itself was calibrated and examined to ensure accurate delivery of stimulus temperature across repeated applications.

Continuous skin temperature data collection was initially piloted to characterise temperature changes at the skin–probe interface during contact with external stimuli. One thermocouple was placed on the forearm skin and another on the surface of the thermal probe. Both a small (1.32 cm^2) and a large (25 cm^2) probe were tested while the probe temperature was set to −5 °C, −10 °C, −15 °C, and −20 °C below resting skin temperature (Figure 19A). This allowed the time-dependent changes in skin temperature during probe contact to be explained. Piloting showed that the lowest temperature the thermal probe could reliably maintain during prolonged (~60 s) skin contact was −20 °C below resting skin temperature. Additional testing involved adding ice to the probe's water tank in an attempt to achieve lower temperatures; however, this approach did not produce stable conditions suitable for the experimental application.

Once the skin temperature profiles were established, a cotton patch saturated with either water or MO was attached to the probe and applied to the skin. Various stimulus–skin profiles were then developed, and a third thermocouple was positioned on top of the cotton patch, ensuring it did not contact the thermocouples on the probe base or the forearm. This configuration enabled measurement of the temperature profile across the skin–patch–probe interface. Skin temperature, probe temperature, and perceived wetness were recorded continuously using the developed VAS system (Figure 19B).

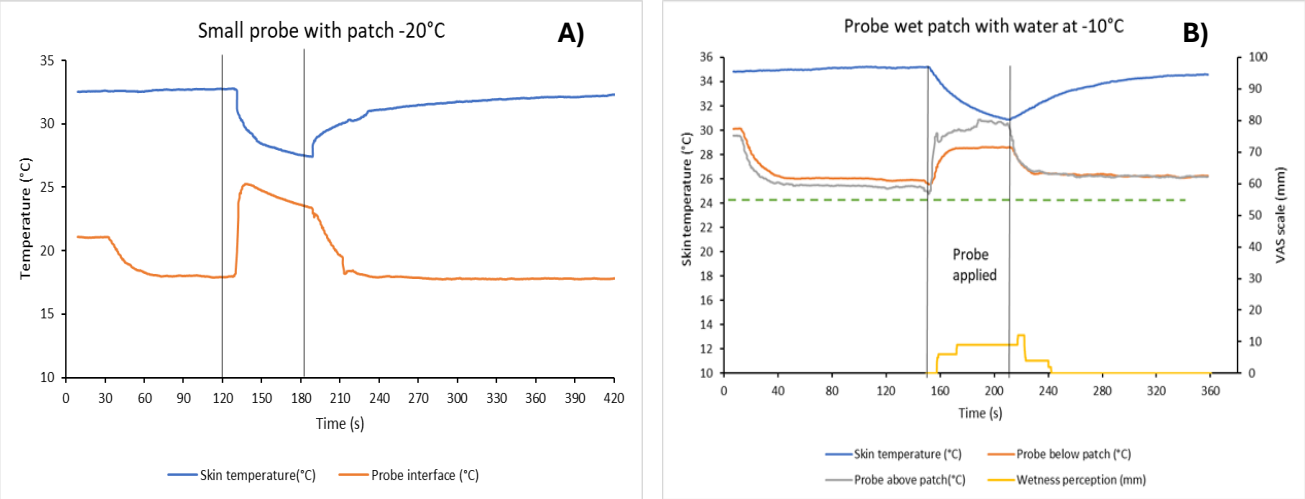

Figure 19. A) Initial piloting of skin and probe temperature. B) Piloting of the skin -patch-probe temperature and concurrent continuous wetness perception assessment.

Once the feasibility of simultaneously measuring skin temperature and wetness perception was established, further pilot testing was conducted to refine the protocol for assessing the c-WPT. These pilots aimed to determine the most appropriate stimulus characteristics and application procedures to reliably evoke measurable biophysical and perceptual responses.

Specifically, a range of fluids were evaluated, including water, MO, and PG, to examine how differences in thermal and physical properties influenced the skin's cooling response and perceived wetness. The temperature of the applied stimuli was also systematically varied between −5 and −20 °C relative to resting skin temperature to identify the temperature capable of producing measurable cooling without compromising participant comfort or probe stability. In addition, piloting was conducted at two anatomical sites—the forearm and the underarm—to assess potential site-specific differences in skin cooling profiles and wetness perception.

Methodological aspects of the protocol were also explored, including the use of repeated stimulus applications and variations in the duration of skin–stimulus contact, in order to establish a procedure that captured the temporal evolution of wetness perception while maintaining experimental consistency. The c-WPT was conceived, designed and tested within the piloting phase, which leveraged and refined the established methodology and for fluid selection contrast for Study 3 - 5 (Chapter 6 - 8). A summary of these pilot investigations is presented, see Table 3.

Table 3. Summary of piloting for the development and process of c-WPT, to assess the interaction between probe and skin temperature, fluid and wetness perception.

Pilot	Material	Fluid	Volume (mL)	Temperature (°C)	Probe size	Application time	Thermocouple	Perception
1	Cotton	Water	1	-5	S	10s	1-skin	No
1	Cotton	Water	1	-10	S	30s	1-skin	No
1	N/A			-5	S	60s	1-skin	No
1	N/A			-10	S	60s	1-skin	No
1	Cotton	Water	1	-5	L	30s	1-skin	No
1	Cotton	Water	1	-10	L	60s	1-skin	No
1	N/A			-5	L	60s	1-skin	No
1	N/A			-10	L	30s	1-skin	No
2	Cotton	Water	1	-5	S	60s	1-skin	Yes
2	Cotton	Water	1	-10	S	60s	1-skin	Yes
2	N/A			-5	S	60s	1-skin	Yes
2	N/A			-10	S	60s	1-skin	Yes
2	Cotton	Water	1	-5	L	60s	1-skin	Yes
2	Cotton	Water	1	-10	L	60s	1-skin	Yes
3	Cotton	Water	1	-5	S	60s	2- skin, probe surface	No
3	Cotton	Water	1	-10	S	60s	2- skin, probe surface	No
3	Cotton	Water	1	-15	S	60s	2- skin, probe surface	No
3	Cotton	Water	1	-20	S	60s	2- skin, probe surface	No
3	Cotton	Water	1	-5	L	60s	2- skin, probe surface	No
3	Cotton	Water	1	-10	L	60s	2- skin, probe surface	No
3	Cotton	Water	1	-15	L	60s	2- skin, probe surface	No
3	Cotton	Water	1	-20	L	60s	2- skin, probe surface	No
4	Cotton	Water	1	-5	L	60s	3- skin, probe surface, above patch	Yes
4	Cotton	Water	1	-10	L	60s	3- skin, probe surface, above patch	Yes
4	Cotton	Water	1	-15	L	60s	3- skin, probe surface, above patch	Yes
4	Cotton	Water	1	-20	L	60s	3- skin, probe surface, above patch	Yes
4	Cotton	PG	0.8	-5	L	60s	3- skin, probe surface, above patch	Yes
4	Cotton	PG	0.8	-10	L	60s	3- skin, probe surface, above patch	Yes
4	Cotton	PG	0.8	-15	L	60s	3- skin, probe surface, above patch	Yes
4	Cotton	PG	0.8	-20	L	60s	3- skin, probe surface, above patch	Yes
5	Cotton	MO	1ml	-15	L	60s	3- skin, probe surface, above patch	No
5	Cotton	MO	1ml	-20	L	60s	3- skin, probe surface, above patch	No

3.4.2 Tactile Threshold Estimation

Tactile sensitivity at the underarm was assessed using Von Fry monofilaments (Figure 20) as they are a simple and inexpensive way to understand the mechanical detection threshold under neutral environmental conditions (Bove, 2006). Each nylon monofilament attached at a right angle to the plastic handle has a precisely calibrated bending force ranging from ~0.008 g to ~300 g, which is placed perpendicular against the skin. The filament buckles at the known force; a limitation to this is user inconsistencies during application. The threshold is defined as the lowest filament force that produces a measurable response. Without looking, the participant will indicate whether they felt the interaction. A staircase method is used, of an ascending or descending pattern depending on the subject's response.

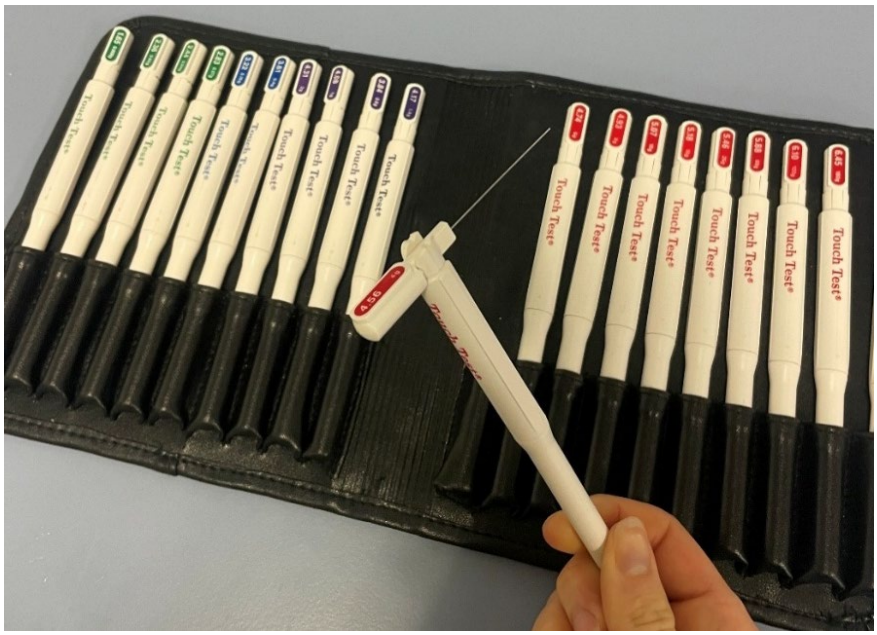

Figure 20. Von Frey monofilaments, which are used to measure tactile thresholds.

3.5 Summary

- ***Bespoke psychophysical framework*:** Across all chapters, wetness perception at the underarm will be assessed using controlled QST, established from stimulus–response paradigm and Bayesian multisensory integration model, enabling systematic manipulation of temperature, fluid properties, hydration state, and hair presence.
- ***Integrated biophysical monitoring*:** Concurrent measurements of local skin temperature (thermocouples, infrared thermography), stratum corneum hydration

(Corneometer), and skin morphology (OCT) will be used to characterise the physiological responses underpinning perceptual changes during and after stimulus application.

- ***Progression from single time-point to temporal assessment*:** Early chapters will employ single time-point VAS, while later chapters will introduce a novel c-WPT to capture the temporal evolution (onset, peak, decay) of wetness during realistic fluid–skin interactions.
- ***Systematic manipulation of fluid thermal properties*:** Experimental chapters will progressively examine how fluid thermal conductivity, heat capacity, and skin biophysical state interact to shape underarm skin cooling and perceived wetness, directly addressing formulation-relevant research and development challenge (Figure 21).

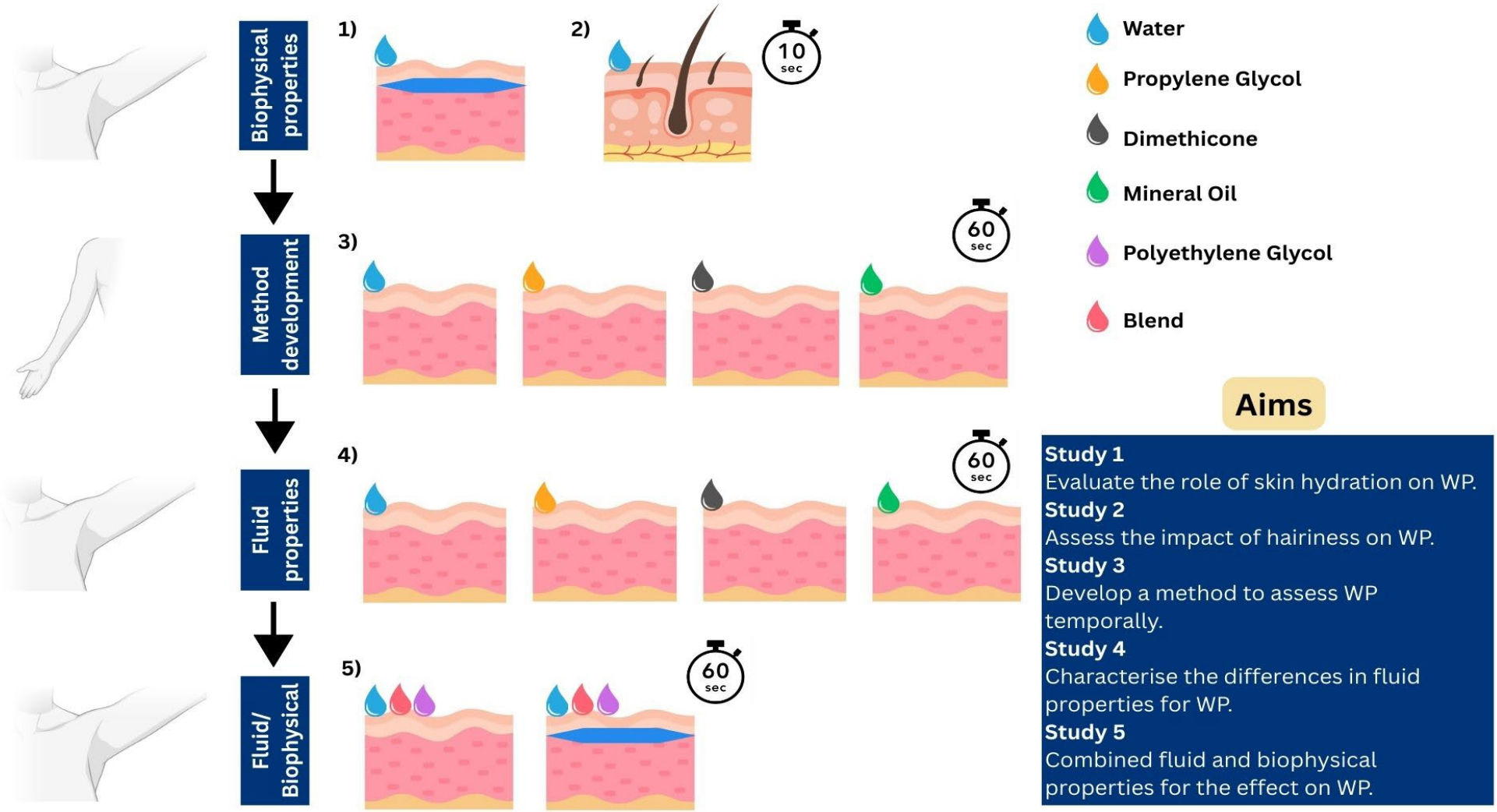

Figure 21. Schematic diagram summarising the experimental methodologies to assess wetness perception during external stimuli contact. *WP = wetness perception*.

Chapter 4 Experimental Study 1: The effects of stimulus temperature and skin hydration on wetness perception at the underarm.

Results from this chapter were published in the peer-reviewed article below:

Ward, J., Verucchi, E., Swaile, D., Parker, K., Worsley, P.R. and Filingeri, D. (2025), Effects of Stimulus Temperature and Skin Hydration Levels on Wetness Perception at the Underarm. Skin Research and Technology, 31, 2-5. https://doi.org/10.1111/srt.70170

4.1 Abstract

Experiencing wetness on the skin because of sweating or contact with fluids can induce thermal discomfort. Millions of people apply APDO products to the underarm to minimise this negative experience. However, the mechanisms underpinning wetness perception at the underarm and the influence of underlying SCH remain underinvestigated. We aimed to evaluate the role of stimulus temperature and skin hydration levels on wetness perception at the underarm in young participants.

Ten healthy participants (5 M / 5 F; 29 ± 7 y) underwent a QST during which they reported the perceived magnitude of wetness perception from a short-duration static application of a cold-wet (i.e., 5 °C below local skin temperature), neutral-wet (i.e. equal to local skin temperature) and warm-wet (i.e., 5 °C above local skin temperature) stimuli. Wetness perception was assessed on a 100-mm VAS (0 = dry; 100 = extremely wet), with a repeated measures design exploring the effects of overhydration (+21 %) and dehydration (-40 %) of the underarm's skin.

Our results indicated a higher wetness perception (p = 0.012) during the cold-wet (40 mm, 95 % CI: +25, +56) than during the warm-wet (25 mm, 95 % CI: +12, +39), and neutral-wet stimuli (24 mm, 95 % CI: +7, +40). Furthermore, overhydration of the underarm' stratum corneum can lead to an increase in wetness perceptions upon contact with cold-wet stimuli only (mean increase: 20 mm, 95 % CI: +3, +36; p = 0.024; corresponding to 20 % increase).

Our findings provide novel fundamental insights into the underarm's perceptual responses to wetness, which could inform understanding of the determinants of wet feel associated with the application of APDO products.

4.2 Introduction

Experiencing wetness on the skin as a result of sweating or contact with fluids has been repeatedly shown to induce thermal discomfort, which is a critical trigger of behavioural responses in humans (Gagge, 1937, Filingeri and Havenith, 2018). Consider, for example, the common experience of wetness at the underarm resulting from thermal or psychogenic sweating. Millions of people apply APDO products to the underarm on a daily basis to minimise this negative experience (Watkinson et al., 2007). APDO are consumer goods hygiene products applied on the underarm to fight odour, reduce sweating and increase self-confidence (Teerasumran et al., 2023). Inefficiencies of APDO action or a lack of application can create visual sweat stains or noticeably wet skin, all of which may negatively impact a person's quality of life (Swaile et al., 2012). Sweat is secreted at the underarm through three different sweat glands, eccrine, apocrine and apoeccrine (Sato et al., 1987, Shelley and Hurley, 1953). The fluid secreted from each type of sweat gland varies based on its functional properties. The apoeccrine and eccrine glands secrete a watery-like fluid, whereas, the apocrine glands produce a viscous, odourless lipid-rich fluid, which, bacteria residing at the underarm react with, resulting in malodour (Low, 2012). Daily application of APDO can minimise sweat secretion and consequently, the malodour (Teerasumran et al., 2023).

APDO have become well-established worldwide and are available in many physical forms and chemical formulations, such as roll-ons, aerosols, sticks and gels (Benohanian, 2001). Whilst generally effective in limiting sweat-induced wetness at the underarm (Teerasumran et al., 2023), these products can trigger undesired wetness perceptions at the point of application, i.e. when a "wet" product at room temperature (~23 °C) contacts the skin of the underarm (which has a likely temperature of ≥ 34 °C). This "acute" wetness experience may negatively impact the acceptability and comfort of such products. Hence, an increased understanding of the mechanisms of wetness perception at the underarm upon contact with a wet stimulus could inform the design of more comfortable APDO.

Extensive psychophysical research in wetness perception has indicated that, due to the likely absence of skin hygroreceptors (Clark and Edholm, 1985), humans learnt to perceive wetness through the integration of thermo-sensory cues. This is triggered by the heat exchange occurring between the skin and a wet stimulus (Filingeri et al., 2014a, Filingeri et al., 2015c), in combination with mechano-sensory cues resulting from moisture moving across the skin surface (Filingeri et al., 2014a, Filingeri et al., 2014d, Filingeri et al., 2015c). Previous work in this area has relied primarily on the application of temperature-modulated wet stimuli (e.g. above, below or equal to skin temperature) with equal moisture contents to various thermally sensitive regions of the body such as the torso (Filingeri et al., 2014a), forehead (Valenza et al., 2019),

neck (Ackerley et al., 2012), lower back (Filingeri et al., 2015d), dorsal foot (Wildgoose et al., 2021), and fingertip (Merrick et al., 2021, Jay and Havenith, 2004). This body of literature has repeatedly demonstrated that a cold-wet stimulus is perceived as wetter than a warm-wet one given the same moisture content (Filingeri et al., 2014a), thereby highlighting the primary role of skin cooling in triggering wetness perceptions.

This observation is particularly relevant in the context of applying a cold-wet APDO to the warm skin of the underarm. However, the extent to which the established perceptual mechanisms for wetness sensing observed across the body also apply to the underarm, due to a lack of psychophysical research specifically testing the underarm. Indeed, the underarm is a unique skin site, where the stratum corneum has reduced barrier function due to personal care regimes, including shaving and APDO application (Turner et al., 2007). Shaving is often associated with sensory irritation from skin damage through artificial, premature removal of skin cells, leading to a thicker epidermis (Chaturvedi et al., 2024). This may impact skin thermal and tactile sensitivity and the resulting wetness perceptions.

Furthermore, SCH levels vary throughout the day via mechanisms of overhydration (e.g. during sweating) and dehydration, and this may alter skin mechanics, such as elasticity, tactile sensitivity and function (Tagami, 2008). Dead stratum corneum cells within the epidermis that are exposed to water solutions, such as during a shower, rehydrate in a two stage process, the initial increase within the first few minutes filling the voids within the most superficial regions of the stratum corneum, followed by a slower linear process of hydration, which induces structural alterations of the stratum corneum and swelling to the corneocytes, leading to increased epidermal hydration and surface area (Gerhardt et al., 2008, Morin et al., 2020). These water-related changes in the stratum corneum modify the chemical structure and mechanical properties of the skin, which in turn may impact tactile sensitivity. Broader evidence indicates that there is a negative correlation between stratum corneum water content and skin roughness (Lee et al., 2022). Indeed, it has been previously reported that hydrated skin decreases the sensation of roughness during contact of the fingertips with textured objects (Verrillo et al., 1998). When considering the relationship between wetness perception and roughness perception, Merrick et al. (2022b) found a negative correlation whereby rougher surfaces felt drier while smoother surfaces felt wetter. However, further research is required to fully establish how the hydration status of the skin of the underarm, and any potential change in skin surface roughness, may impact local wetness sensitivity on this skin site.

Altogether, the evidence above highlights our limited understanding of the mechanisms underlying wetness perception at the underarm and their variation with changes in the hydration levels of the stratum corneum. Therefore, the aim of this study was to investigate the role of

stimulus temperature and skin hydration levels on wetness perception at the underarm in healthy young participants. We hypothesised that wetness perceptions will be greater as a result of cold-wet stimulus application as well as with increases in SCH.

4.3 Materials and Methods

This study was approved by the University of Southampton Ethics Committee (approval no.73017). All participants provided written informed consent prior to testing. The study conformed to the ethical standards set by the Declaration of Helsinki.

Participants

Ten healthy recreationally active participants (5 M / 5 F; age 28.8 ± 7.2 years; height 171.3 ± 9.5 cm; body mass 78.1 ± 18.2 kg; BMI 26.4 ± 4.2 kg/m^2) were recruited for the study. Priori sample size calculation was performed using an effect size corresponding to f = 0.71 (Filingeri et al., 2013b), combined with an $\alpha = 0.05$ and a β (power) = 0.8, determined a minimum sample of seven participants. Ten participants were recruited in case of loss to follow-up.

The volunteers had no history of sensory-related disorders nor cardiovascular, neurological, or skin-related conditions (e.g., eczema). Participants were provided with specific instructions prior to testing, including refraining from applying APDO, and they were required to shave their underarms 24 hours prior to the testing sessions. Female participants also provided self-reports of the last day of their most recent menstrual cycle in relation to the testing day.

Experimental Design

The study was a single-blind, randomised crossover design. Participants took part in two testing sessions on separate days, separated by a minimum of 24 hours, performed under the same thermo-neutral ambient conditions (25 °C and 45 % relative humidity). During the sessions, participants performed a standardised QST (Valenza et al., 2019), which consisted in having to report on a VAS the magnitude of wetness perception arising from the local application of warm-, neutral- and cold-wet stimuli to the skin of the underarm. This was performed under baseline conditions as well as following a local overhydration and dehydration protocol of the stratum corneum. Biophysical skin assessments were also performed to characterise local skin properties.

The dehydration/overhydration protocols were developed following extensive pilot studies. They consisted of a) the application of a 50 cm^2 cotton patch, fully saturated with room-temperature water (0.1 mL). The patch was covered and secured to the skin with impermeable adhesive tape to prevent evaporation and left in place for 30 minutes to achieve local overhydration; b) the application of calcium-carbonate powder (0.025 g) on the skin side for 30 minutes for dehydration. Pilot studies indicated this experimental approach induced changes in local SCH of ~30 % from baseline.

It is important to note that the application of the QST at the underarm under dehydration and overhydration skin states required some adjustment from previous studies to minimise the potential carry-over effect following wet probe application within the same testing session. As such, the centre of the underarm was partitioned into three areas, each of which was stimulated by a different temperature stimulus (i.e. cold-wet, 5 °C below local skin temperature; neutral-wet, equal temperature as local skin temperature; and warm-wet, 5 °C above local skin temperature). The application area was randomised between participants to minimise any bias due to skin site effects on temperature-dependent wetness perceptions. Participants were also blinded to the temperature of the stimuli to limit expectation bias. The same investigator performed all testing.

Experimental Procedures

Upon arrival at the laboratory, participants' anthropometric measurements were collected. Height was measured on a wall stadiometer and weight on a precision scale (KERN 150K2DL, Balingen, Germany). Participants were then positioned supine on a therapy bed, and the testing sites were marked with a washable marker. Subsequently, participants were familiarised with the QST and VAS using the forearm as a neutral test site (i.e., the midpoint between the wrist and antecubital fossa). Familiarisation procedures have been extensively reported in our previous paper (Valenza et al., 2019).

Upon completion of the familiarisation phase, testing commenced. First, we collected a series of biophysical skin parameters at the underarm with non-invasive methods, including assessments of local SCH (Clarys et al., 2012) (Corneometer; CM 825, CK Electronics, Germany), and of surface roughness (i.e. Rq = the root mean square variation of the surface height, acquired using an OCT, VivoSight DX, Michelson Diagnostics, UK). SCH was measured at each stimulation site, the Corneometer measures the capacitance of the skin surface through the electromagnetic contact in the probe during the spring displacement and converted into arbitrary units (Westermann et al., 2020, Anthonissen et al., 2015). The higher the water content in the stratum corneum, the greater the capacitance, leading to high readings. It is of note that

changes in skin temperature may affect the water mobility and dielectric properties in the skin (Rossmann and Haemmerich, 2014), however, the initial hydration stage is unaffected by temperature, whereas the second stage showed a temperature-dependent increase above 42 °C (Morin et al., 2020). When considering the skin temperature data collected during our study, we found minimal variation in this parameter between days and across participants (Visit 1: 34.6 ± 1.5 °C, Visit 2: 34.0 ± 1.2 °C). Hence, it is unlikely that our measurements of skin hydration would have been impacted by skin temperature. Whereas surface roughness was measured only at the centre of the underarm. Following these measurements, tactile detection thresholds at the underarm were measured using Von Frey's monofilaments (North Coast Medical, Inc., Morgan Hill, LA, USA) employing the up-down method (Chaplan et al., 1994, Dixon, 1965). At this point, the QST of wetness perception was performed. This consisted of a 10 second application of a hand-held temperature-controllable probe (surface area: 1.32 cm^2), mounted with a 100 % cotton patch wetted with 0.8 mL of water, randomised to one of the three marked areas of the underarm. The area stimulated was dependent on the pre-determined temperature of the stimulus, which was either cold-wet (5 °C below local skin temperature), neutral-wet (equal temperature as local skin temperature) or warm-wet (5 °C above local skin temperature). Stimulus' temperature was relative to local skin temperature, which was assessed using infrared thermometry (Spot IR Thermometer TG54; FLIR Systems, Wilsonville, OR, USA). Upon application of the wet stimulus, participants were verbally encouraged to report their local thermal and wetness perceptions on separate VAS [i.e. 100-mm wetness scale with anchor points: dry (0) to extremely wet (100); and 200-mm thermal scale with anchor points: very cold (0), neutral (100) and very hot (200)]. The three temperature stimuli were applied in a randomised order with 60 seconds in between applications.

Upon completion of the baseline QST, and depending on the testing session, the skin of the underarm underwent the 30-minute overhydration or dehydration protocol described in the section above. Upon completion of the protocol, the same sequence of biophysical assessments (i.e. local skin temperature, SCH, skin roughness, tactile sensitivity) and the same QST of wetness were performed on the same underarm sites to establish hydration-dependent changes in wetness perceptions and their biophysical correlates, for a schematic of the experimental procedure, see Figure 22.

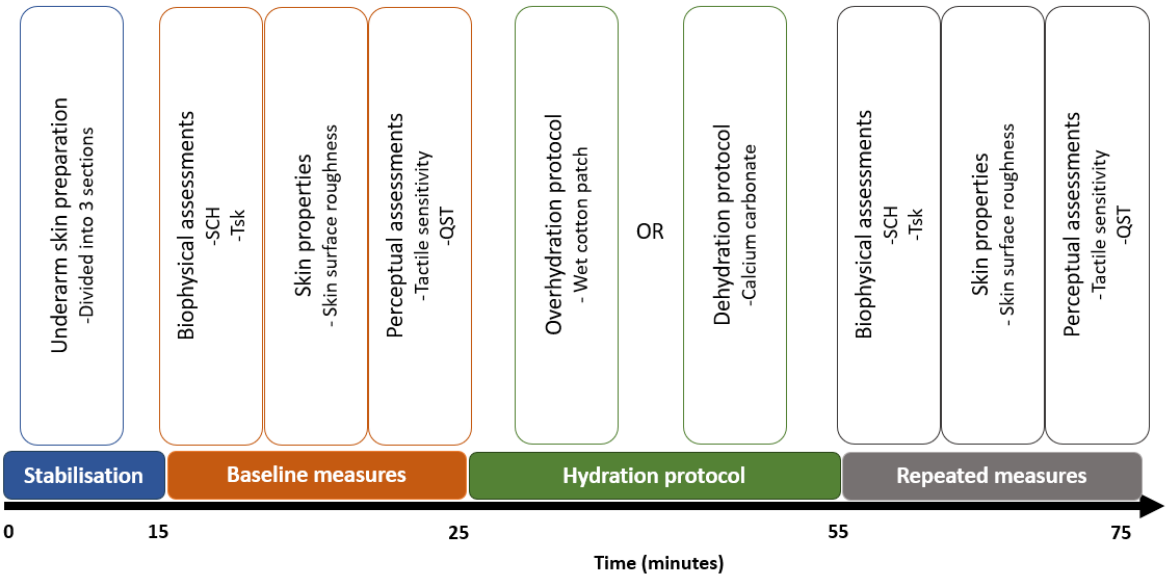

Figure 22. Schematic of experimental design in order of events. *SCH = stratum corneum hydration, Tsk = skin temperature, QST = quantitative sensory test.*

Statistical Analysis

Data normality and homoscedasticity were assessed using the Shapiro–Wilk and Levene tests, respectively. SCH, wetness perception and thermal sensation data were identified to be normally distributed, hence parametric tests were used for analysis. SCH, wetness perception and thermal sensation data were analysed separately for the overhydration and dehydration sessions by means of 2-way repeated measures ANOVAs [independent variables: i) time, with two levels, i.e. prior and following hydration protocol; ii) skin site for stimulation, with three levels, i.e. warm-wet site, neutral-wet site and cold-wet site)] to determine how skin hydration varied following on each protocol and across testing sites. In the event of a statistically significant main effect or interaction, a post hoc analysis was conducted using a Bonferroni correction. Skin surface roughness data were identified to be normally distributed, paired sample T-test with Bonferroni correction were used to assess overhydration and dehydration outcomes.

Tactile sensitivity data were identified to be non-normally distributed, thus non-parametric test were used. Tactile sensitivity data were analysed separately for the overhydration and dehydration sessions by means of Friedman tests followed by [independent variables: i) time, with two levels, i.e. prior and following hydration protocol; ii) skin site for stimulation, with three levels, i.e. warm-wet site, neutral-wet site and cold-wet site)] to determine how tactile sensitivity varied following each protocol and across testing sites. In the event of a statistically

significant main effect, a post-hoc analysis was conducted using Wilcoxon signed-ranks tests with a Bonferroni correction.

All data was analysed using Statistical package for the social sciences 19 (SPSS, version 28.1, Chicago, USA). Statistical significance was set at $p < 0.05$, and data were reported as means, standard deviation (SD) and 95 % Confidence Intervals (CI).

4.4 Results

Stratum Corneum Hydration and Skin Surface Roughness

Regarding SCH during the overhydration protocol, a statistically significant effect of time (F = 10.53, $p = 0.010$), yet no effect of skin site for stimulation (F = 3.25, $p = 0.074$) nor an interaction (F = 0.92, $p = 0.883$) was found. Specifically, when collapsed over skin site for stimulation, SCH increased by 10.0 au (95 % CI: +3.1, +16.7, $p = 0.010$) from a baseline value of 47.6 au (95 % CI: +37.4, +57.8) to a post-overhydration value of 57.5 au (95 % CI: +43.9, +71.0). This corresponded to an average increase in SCH of 21 % (Figure 23A).

During the dehydration protocol, SCH significantly changed over time (F = 32.34, $p < 0.001$), with no effect of skin site for stimulation (F = 3.73, $p = 0.083$), and an interaction effect (F = 5.67, $p = 0.030$). When collapsed over the skin site for stimulation, SCH decreased by 22.4 au (95 % CI: +13.5, +31.4, $p < 0.001$) from a baseline value of 50.9 au (95 % CI: +37.6, +64.2) to a post-dehydration value of 28.4 au (95 % CI: +17.1, +39.8). This corresponded to an average decrease in SCH of 44 % (Figure 23B). Yet, the interaction effect indicated that this average decrease was less pronounced at the neutral-wet site of stimulation (-10 au, 95 % CI: -23.2, +1.5, $p = 0.078$) than at the warm-wet (-31.2 au, 95 % CI: -45.6, -16.8, $p < 0.001$) and cold-wet sites (-25.2 au, 95 % CI: -33.9, -16.5, $p < 0.001$).

Surface roughness had no statistically significant difference between baseline (Rq = 0.021 ± 0.005 µm) and post-hydration values (Rq = 0.023 ± 0.005 µm; $t = -0.965$, $p = 0.367$) nor dehydration values (Rq = 0.022 ± 0.004 µm; $t = 0.211$, $p = 0.840$).

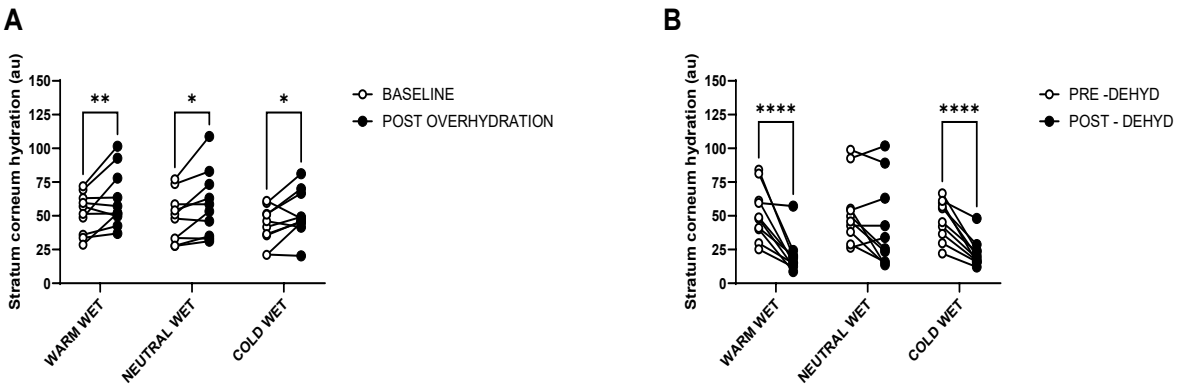

Figure 23. Changes in stratum corneum hydration from baseline to post overhydration (A) and dehydration (B) protocols in the warm-wet, neutral-wet and cold-wet sites at the underarm. *Statistical significance $p < 0.05$.

Wetness Perceptions

Regarding wetness perception data during the overhydration protocol, we found a statistically significant effect of time (F = 7.21, $p = 0.025$), of wet stimulus temperature (F = 5.16, $p = 0.020$), and an interaction (F = 3.63, $p = 0.047$). Specifically, the interaction effect indicated that wetness perceptions increased following the overhydration protocol as a result of the cold-wet stimulus application only (mean increase: 20 mm, 95 % CI: +3, +36; $p = 0.024$). This corresponded to an average increase in cold-wet perception of ~20 % above baseline (Figure 24A, B). Regarding wetness perception data during the dehydration protocol, we found no statistically significant effect of time (F = 1.14, $p = 0.312$), a statistically significant effect of wet stimulus temperature (F = 6.83, $p = 0.012$), and no interaction (F = 1.07, $p = 0.352$). Specifically, when collapsed over time, wetness perceptions were wetter during the cold-wet stimulation (40 mm, 95 % CI: +25, +56) than during the warm-wet (25 mm, 95 % CI: +12, +39), and neutral-wet stimulation (24 mm, 95 % CI: +7, +40) (Figure 24C, D).

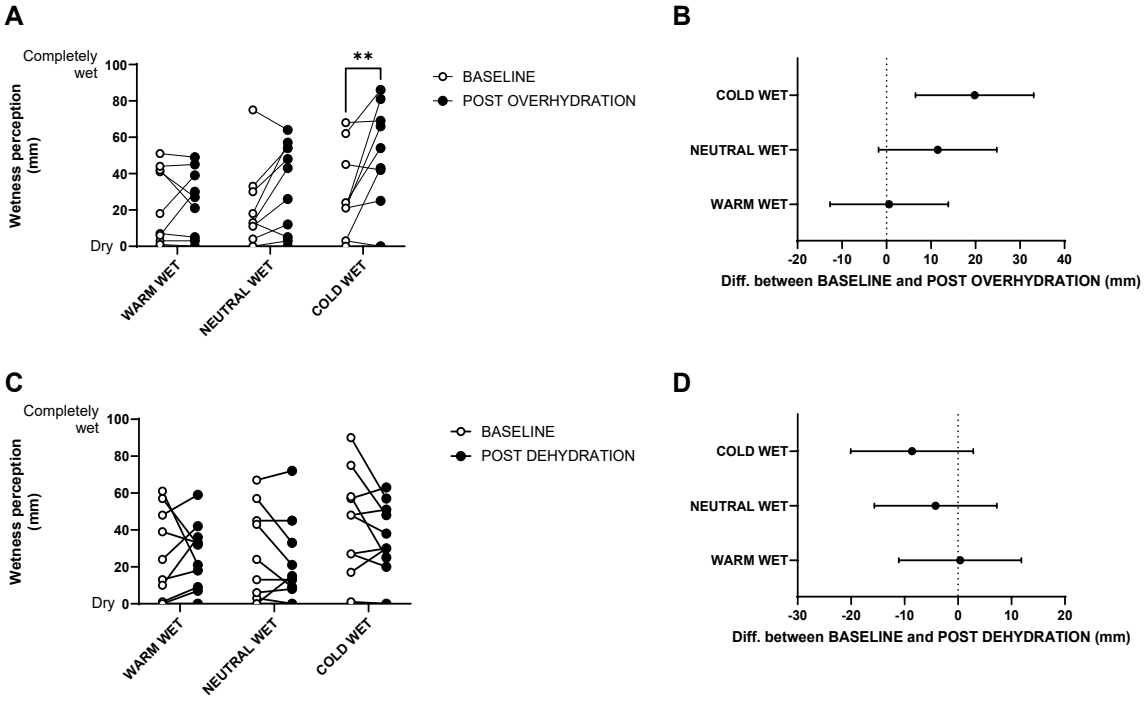

Figure 24. Changes in wetness perception from baseline to post overhydration (A) and dehydration (C) protocols in the warm-wet, neutral-wet and cold-wet sites at the underarm. *Statistical significance $p < 0.05$. 95 % confidence intervals for the warm-wet, neutral-wet and cold-wet sites for overhydration (B) and dehydration (D) report.

Thermal and Tactile Sensations

Regarding thermal sensation data during the overhydration protocol, we found no statistically significant effect of time (F = 0.17, $p = 0.683$), a statistically significant effect of wet stimulus temperature (F = 24.94, $p < 0.001$), and no interaction (F = 1.15, $p = 0.339$). Specifically, when collapsed over time, thermal sensations were warmer during the warm-wet stimulation (119 mm, 95 % CI: +107, +131), colder during the cold-wet stimulation (63 mm, 95 % CI: +49, +78), and close to neutrality during the neutral-wet stimulation (109 mm, 95 % CI: +95, +123) (Figure 25A). During the dehydration protocol there was no statistically significant effect of time (F = 0.24, $p = 0.630$), a statistically significant effect of wet stimulus temperature (F = 13.26, $p < 0.001$), and no interaction (F = 2.23, $p = 0.147$). Specifically, when collapsed over time, thermal sensations were warmer during the warm-wet stimulation (112 mm, 95 % CI: +86, +138), colder during the cold-wet stimulation (58 mm, 95 % CI: +41, +75), and close to neutrality during the neutral-wet stimulation (92 mm, 95 % CI: +76, +108) (Figure 25B).

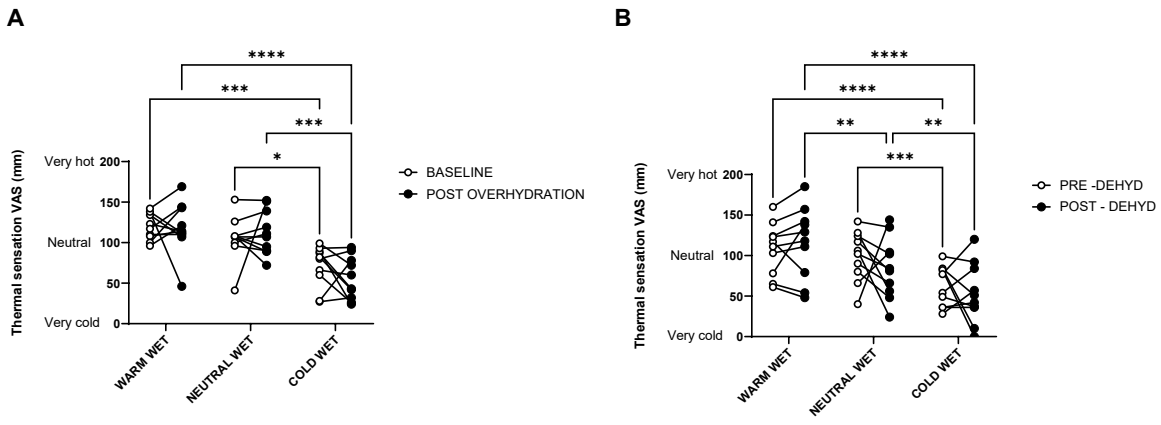

Figure 25. Changes in thermal sensitivity from baseline to post overhydration (A) and dehydration (B) protocols in the warm-wet, neutral-wet and cold-wet sites at the underarm. *Statistical significance $p < 0.05$.

Regarding tactile sensitivity data, we found no statistically significant effect of time nor skin site for stimulation for overhydration (Chi square = 1.179, $p = 0.877$) and dehydration (Chi square = 7.597, $p = 0.180$).

4.5 Discussion

The study aimed to investigate the role of stimulus temperature and skin hydration levels on wetness perception at the underarm in healthy young participants. We hypothesised that wetness perceptions at the underarm will be greater as a result of cold-wet stimulus application as well as with increases in SCH. Our findings supported both our hypotheses. First, we observed that, whether applied on normo-, over- or de-hydrated skin, cold-wet stimuli triggered wetter perceptions at the underarm than warm- and neutral-wet stimuli. Second, we found that an increase in SCH of ~21 % was associated with a ~20 % increase in wetness perception only when a cold-wet stimulus was applied on the skin of the underarm. These findings provide novel fundamental insights into the underarm's perceptual responses to wetness, which could inform understanding of the determinants of wet feel associated with the application of APDO products.

Regarding our first observation, our findings are in line with previous research that has indicated that, given the same moisture content, cold-wet stimuli consistently trigger wetter perceptions than warm- and neutral-wet test conditions (Valenza et al., 2019, Filingeri et al., 2013b, Filingeri et al., 2014c, Wildgoose et al., 2021, Jay and Havenith, 2004, Ackerley et al., 2012). Filingeri et al. (2013b) has previously reported that a cold-dry stimulus can elicit a perception of skin

wetness, highlighting the importance of skin cooling as a mechanism for the detection of wetness in the absence of a skin hygroreceptor. On the contrary, warmth appears to suppress the perception of wetness when in contact with a wet stimulus (Filingeri et al., 2015d, Filingeri et al., 2014d, Christogianni et al., 2022). Our current findings confirm that such specific perceptual mechanisms for wetness perception also apply to the skin of the underarm, which is a unique skin site due to its anatomy and biophysical properties resulting from personal care regimes, including shaving and APDO application (Turner et al., 2007). Importantly, our findings extend previous work to demonstrate that the role of coldness in driving wetness perception is maintained irrespective of SCH levels (i.e. from 44 % dehydration to 21 % overhydration).

Regarding our second observation, our findings provide novel evidence that an increase in local SCH of ~21 % is associated with an increase in wetness perception during cold-wet stimulation of the underarm. It has been previously suggested that an increase in water content of the stratum corneum could induce swelling of the corneocytes with consequent changes in the mechanical properties of the skin (Warner et al., 2003) such as friction, pliability and thermal conductivity (Draelos, 2009). It has also been suggested that overhydration may increase skin contact area, in turn leading to an increase in tactile sensitivity (Samadi et al., 2022). Verrillo et al. (1998) also observed that skin dehydration impacted the perception of textured roughness by decreasing tactile sensitivity. Due to the importance of thermal conductivity, tactile sensitivity, and contact area in skin wetness perception, it was expected that such mechanisms would underlie the hypothesised increase in wetness perception with overhydration of the stratum corneum. Despite not observing any overhydration-induced changes in skin surface roughness, tactile sensitivity, or thermal sensation at the underarm, the underlying mechanisms for an increase in cold-wetness perception with overhydration remain unclear. The underarm, being a naturally warm and moist environment that undergoes frequent tactile interactions (such as from clothing and sweat), may be pre-conditioned, which could reduce the sensitivity to these effects. Additionally, repeated moisture exposure can alter the structural integrity of the corneocytes, impacting their maturity, turnover rate, and thickening of the stratum corneum (Wickett and Visscher, 2006). This adaptation could contribute to the lack of significant biophysical and anatomical changes observed under the overhydration protocol. Further investigation is needed to fully understand these dynamics.

Nevertheless, and from an applied standpoint, these observations are important to drive innovation in APDO design. Our findings support the view that these products can trigger undesired wetness perceptions at the point of application, i.e. when a (cold) “wet” product at room temperature (~23 °C) contacts the skin of the underarm (34.6 ± 1.5 °C). Furthermore, our findings indicate that such cold-wet perceptions may be further increased when APDO application occurs on overhydrated skin. This scenario is commonly associated with the status

of the skin following a shower, which is also a common application time for APDO products. Future developments of these products should, therefore, consider approaches to minimise cold-inducing wetness perceptions upon contact with the overhydrated skin of the underarm, as this scenario is likely to trigger the most intense cold-wet perceptions.

Whilst the findings of this study have relevant applied implications, there are also some study limitations that are worth highlighting. For example, individual variations in the shape of the underarm may impact specific perceptual outcomes as a result of individual variability in contact area during both hydration manipulations and wet stimulus applications. The chemical composition of fluids in APDO affects their thermal conductivity, potentially altering skin cooling rates upon contact (Bergmann Tiest and Kappers, 2009). Skin cooling is known to enhance wetness perception (Filingeri et al., 2013b). However, the relationship between a fluid's thermal conductivity and wetness perceptions is not fully understood. Future studies should therefore also consider how the current findings may vary when fluid application extends beyond water to include fluids likely found in the chemical formulations of commercially available APDO. As these fluids may present varying heat capacity and thermal conductivity properties, it is reasonable to expect that their application may differentially impact wetness perceptions upon contact with the underarm.

4.6 Conclusion

In conclusion, we have demonstrated that the established perceptual mechanisms underlying wetness perception in healthy young adults also apply to the skin of the underarm, as we found that cold-wet stimuli were consistently reported to be wetter than warm- and neutral-wet ones when applied to either normally hydrated as well as over- and dehydrated skin. Furthermore, we provide novel evidence that overhydration of the underarm' stratum corneum can lead to an increase in wetness perceptions upon contact with cold-wet stimuli. These observations carry applied implications to inform the design of APDO that minimise wet perceptions upon contact and help improve users' comfort.

Chapter 5 Experimental Study 2: The impact of hair on local skin wetness perception at the underarm during static and dynamic applications of cold-wet stimuli.

Results from this chapter were under review in the peer-reviewed article below:

Ward, J., Martin, J., Swaile, D., Parker, K., Cochran, B., Worsley, P., Filingeri, D. (2026). The impact of hair on local skin wetness perception at the underarm during static and dynamic applications of cold-wet stimuli. The Journal of Sensory Studies.

5.1 Abstract

Previous research has highlighted differences in wetness perception between hairy and glabrous skin regions; yet it is unclear how wetness perception differs at the same body region, such as the underarm, in the presence and absence of hair. This study aimed to investigate the impact of hair on local wetness perception at the underarm to inform the design of APDO.

Ten healthy males (21 ± 2 y) underwent a QST of wetness perception and thermal sensation on hairy (right-side) and shaven (left-side) underarm skin, whereby they reported on a 100-mm VAS the magnitude of wetness perception (0 = dry; 100 = extremely wet) and thermal sensation (0 = very cold; 100 = neutral; 200 = very hot). Five applications of a wet temperature-controlled probe (23 °C; 0.8 ml water; 1.32 cm^2) were applied both statically (10 s) and dynamically (4 x forward-backwards motions).

The results indicated a statistically significant interaction between hairiness and mode of application on wetness perception (p = 0.036), such that: a) during static applications, wetness perceptions were greater under shaven vs. hairy conditions (+18.5 mm, 95 % CI: +1.5, +35.5; p = 0.036; ~20 % difference); b) wetness perceptions were greater during dynamic vs. static applications under hairy conditions only (+19.0 mm, 95 % CI: +6, +32; p = 0.008; ~20 % difference).

Our study provides novel empirical evidence that underarm hairs could modulate wetness perception, acting as potential “thermal insulators” under static wet applications, and as “perception enhancers” under dynamic wet interactions. These findings expand our

understanding of the thermal and tactile determinants of the “wet feel” resulting from the application of APDO products at the underarm skin.

5.2 Introduction

Experiencing wetness on the skin, whether from sweating or contact with external fluids, has been recognised as a source of thermal discomfort and a key driver of behavioural thermoregulation in humans (Filingeri and Havenith, 2018, Gagge, 1937). A common example is the perception of wetness at the underarm resulting from thermal or psychogenic sweating. To mitigate the discomfort arising from this experience, millions of individuals worldwide apply APDO daily to reduce sweat production, control odour, and enhance self-confidence (Watkinson et al., 2007, Teerasumran et al., 2023). Uncontrolled sweating, or the absence of product use, can lead to visible sweat marks, moist skin, and malodour—all of which may negatively affect quality of life (Swaile et al., 2012).

APDO are available globally in various physical forms and chemical formulations, including roll-ons, aerosols, sticks, and gels (Benohanian, 2001). While these products are generally effective in limiting sweat-induced wetness (Teerasumran et al., 2023), they can also induce transient cooling-induced wetness perceptions upon contact with the skin, given that products’ temperature (i.e., ~23 °C) is often lower than typical skin temperature (i.e., ~34 °C). As this perceptual response can influence product acceptability and comfort, a greater understanding of the mechanisms underlying wetness perception at the underarm, particularly during contact with cold-wet stimuli, is therefore essential to inform the design of more comfortable APDO.

The underarm is a unique skin site characterised by a variety of structures, including sweat glands [i.e. three distinct gland types: eccrine, apocrine, and apoeccrine (Sato et al., 1987, Shelley and Hurley, 1953)] and hairs (Buffoli et al., 2014, Weddell et al., 1954). Hairy skin is innervated by a network of sensory afferents important for the sense of touch. The hair follicles are innervated by myelinated fast-conducting Aβ and Aδ fibres, slowly adapting type I and type II receptors, and rapidly adapting receptors. As well as, the human skin and close receptive fields are innervated by unmyelinated slow-conducting low-threshold mechanoreceptors known as C-tactile afferents (Ackerley et al., 2014b, McGlone et al., 2014, Moore et al., 2025). These afferents are likely to respond to external mechanical stimuli, including sweat running across the skin and/or hair deflection during contact with external stimuli (e.g. application of APDO) (Ackerley et al., 2014b).

Concerning wetness perception, extensive psychophysiological research has indicated that, in the absence of wetness-sensing receptors (Clark and Edholm, 1985), humans perceive wetness through the integration of our somatosensory system, combining thermo-sensory, triggered by the heat exchange occurring between the skin and a wet stimulus (Filingeri et al., 2014a, Filingeri et al., 2015c), and mechano-sensory cues, resulting from moisture moving across the skin surface (Filingeri et al., 2014a, Filingeri et al., 2014d, Filingeri et al., 2015c). A body of literature has repeatedly demonstrated that during a static application to the skin, a cold-wet stimulus is perceived as wetter than a warm-wet one for the same moisture content (Filingeri et al., 2014a), thereby highlighting the primary role of skin cooling in triggering wetness perceptions. Conversely, when the stimulus is applied dynamically across the skin, the perception of wetness increases with movement, irrespective of temperature (Filingeri et al., 2014b). This evidence has indicated that wetness perceptions are greatest in magnitude during contact with a cold-wet stimulus that moves dynamically across the skin. This scenario is similar to that of an APDO application, whereby skin cooling and (hair-mediated) tactile cues are generated (Filingeri and Ackerley, 2017).

Our group has recently demonstrated the importance of local skin cooling in triggering wetness perceptions at the underarm (Ward et al., 2025). However, it remains to be established the extent to which tactile cues, as mediated by the presence of hairs at the underarm, also contribute to the perception of wetness during the application of APDO. Indeed, the presence of hairs could modulate thermal cues at the underarm by slowing the rate of sweat evaporation or by reducing the degree of skin cooling upon direct fluid contact with the skin (Ackerley et al., 2012, Filingeri and Havenith, 2015).

Previous research has highlighted differences in wetness perception between hairy (i.e. non-glabrous) and glabrous skin regions of the body; yet it is unclear how local wetness perception differs at the same body region, such as the underarm, in the presence and absence (i.e. shaven) of hairs. Ackerley et al. (2012) has previously reported no differences in wetness sensitivity across hairy and glabrous skin sites, including the glabrous palm of the hand, despite the latter presents a higher density of mechanoreceptors. On the other hand, Filingeri et al. (2014b) provided preliminary evidence of differences in wetness perception between hairy and glabrous skin sites. In their study, the protocol involved either a cold-wet, neutral-wet, or warm-wet stimulus, presented either statically (i.e., only thermal cues available) or dynamically (i.e., both thermal and tactile cues available), on either a glabrous skin site (finger pad) or a hairy skin site (ventral side of the forearm). They found a significant trend whereby a greater perception of wetness was experienced over the hairy than the glabrous skin site. Indeed, different hair follicle types are observed across specific skin sites; for example, the scalp and underarm present hormone-dependent terminal hair shafts, which are longer and thicker than the vellus

hair (androgen-independent) found in sites such as the forearm (Buffoli et al., 2014). In this respect, one study has previously observed differences in scalp sensitivity to cold stimuli applications between hairy and shaven skin, whereby a shaven scalp was found to be more sensitive to cold than a hairy one (Mehrabyan et al., 2011). Yet, to our understanding, there is no evidence on the sensitivity differences to cold stimuli applications on hairy and shaven skin of the underarm.

Overall, the evidence above highlights our uncertainty regarding the extent by which skin properties, including the presence of hairs, may impact wetness perception. This lack of knowledge is particularly concerned with skin sites such as the underarm. This study aimed to investigate the impact of hairs on local skin wetness perception at the underarm to inform the design of APDO. We hypothesised that the presence of hairs may: 1) reduce wetness perceptions under static cold-wet applications at the underarm (i.e. insulative effect of hairs); and 2) increase wetness perceptions during dynamic cold-wet stimulations (i.e. enhanced hair-mediated tactile feedback).

5.3 Materials and Methods

The testing procedures were explained to all volunteers, who gave written informed consent prior to participation. The University of Southampton Ethical Committee approved the research study (no.73017). All procedures were conducted in accordance with the principles outlined in the Declaration of Helsinki.

Participants

Ten non-smoking, physically active males (21 ± 2 yrs; 182 ± 12 cm; 74 ± 10 kg) who did not regularly remove their underarm hair were recruited for a randomised single-blind crossover study. Priori sample size calculation was performed using an effect size corresponding to f = 0.71 (Filingeri et al., 2013), combined with an $\alpha = 0.05$ and a β (power) = 0.8, determined a minimum sample of seven participants. Ten participants were recruited to accommodate dropouts.

The volunteers had no history of sensory-related disorders or cardiovascular, neurological, or skin-related conditions (e.g., eczema). In preparation, participants refrained from applying APDO and were required to shave the hair of one of their underarms 24 hours prior to testing, and to keep the hairs on the other underarm. The underarm hair was completely removed using

a handheld razor provided, ensuring the underarm skin was fully exposed. If there was any evidence of skin damage or irritation from shaving, then the participants had to return after a further 24 hours.

Experimental Design

Participants took part in one testing session and a familiarisation session on separate days, separated by a minimum of 24 hours, performed under the same thermo-neutral ambient conditions (25 °C and 45 % relative humidity). During the sessions, participants performed a standardised QST (Ward et al., 2025), which consisted of having to report on a VAS the magnitude of wetness perception and thermal sensation arising from the local application of a cold-wet stimulus to the skin of the underarm. This was performed under two conditions; either with hairy (right-side) or shaven (left-side) underarm skin.

Experimental Procedures

Upon arrival to the laboratory, participants' anthropometric measurements were collected. Height was measured on a wall stadiometer and weight on a precision scale (KERN 150K2DL, Balingen, Germany). Participants were positioned supine on a therapy bed, and the testing site was marked with a washable marker. Subsequently, participants were familiarised with the QST and VAS using the forearm as a neutral test site (i.e., the midpoint between the wrist and antecubital fossa). Familiarisation procedures have been extensively reported in our previous paper (Ward et al., 2025).

Upon completion of the familiarisation phase, testing commenced. First, local skin temperature in the centre of the underarm was measured using infrared thermometry (Spot IR Thermometer TG54; FLIR Systems, Wilsonville, OR, USA). This was performed before application and upon removal of the probe, to ensure skin temperature had returned to baseline before the next application. At this point, the QST of wetness perception and thermal sensation was performed. This consisted of a static 10 s application of a hand-held temperature-controllable probe (surface area: 1.32 cm^2; 23 °C), mounted with a 100 % cotton patch wetted with 0.8 mL of water, then followed by a dynamically applied (4 x forward-backwards motions). The distance between the two points was measured by finding the middle of the underarm (over the midaxillary line, 10 cm above the nipple line) and marking 5 cm distally towards the upper arm and 5 cm inferiorly towards the ribs. Application pressure was not measured but was controlled to be sufficient to ensure complete contact, at the same time not resulting in pronounced skin indentation.

Upon application of the cold-wet stimulus, participants were verbally encouraged to report their local thermal and wetness perceptions on separate VAS [i.e. 100-mm wetness scale with anchor points: dry (0) to extremely wet (100); and 200-mm thermal scale with anchor points: very cold (0), neutral (100) and very hot (200) Figure 26]. The stimulus was applied five times per mode of application (static and dynamic) and was alternated between each underarm (hairy and shaven) for a total of 20 applications with 60 seconds between each (Figure 27). When considering static estimate threshold testing, a single application is sufficient, yet for a dynamic application, repeated stimulus application is recommended for improved reliability and inter-and-intra comparability (Chen et al., 2025, Marcuzzi et al., 2017), therefore, for consistency in the analysis of the results, repeated applications were employed.

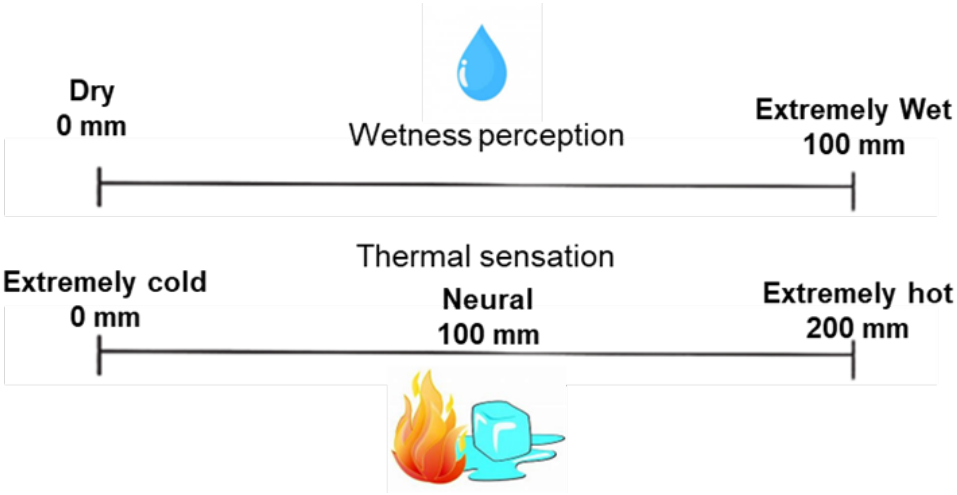

Figure 26. Visual analogue scale for wetness perception (top) and thermal sensation (bottom) used for the quantitative sensory testing during contact with the cold-wet stimulus.

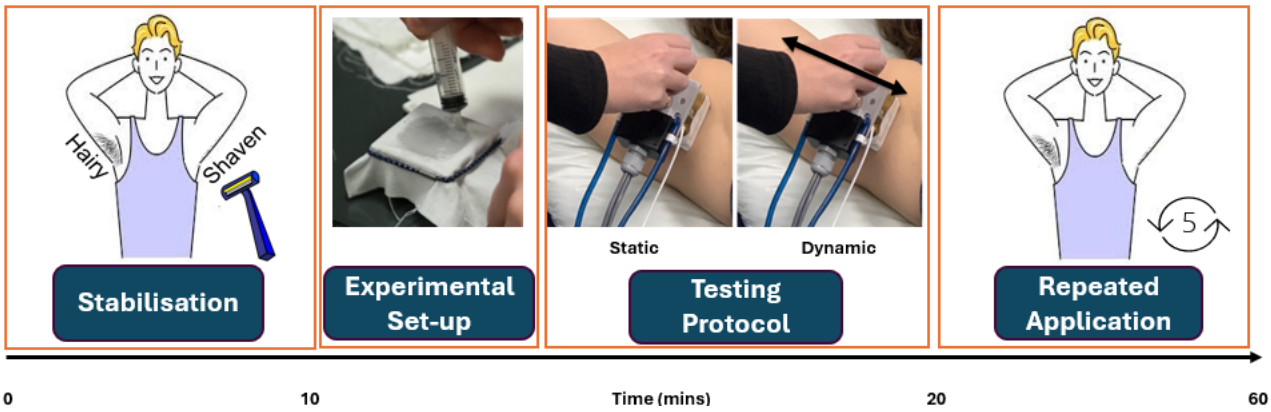

Figure 27. Schematic of experimental design in order of events.

Statistical Analysis

Data normality and homoscedasticity were assessed using the Shapiro–Wilk and Levene tests, respectively. Wetness perception and thermal sensation data were identified to be normally distributed, hence parametric tests were used for analysis. Wetness perception and thermal sensation data were analysed separately by means of 2-way repeated measures ANOVAs [independent variables: i) hairiness, with two levels, i.e. hairy vs shaven; ii) mode of application, with two levels, i.e. static vs dynamic)] to determine how the perceptual measures varied following on each mode of application and across hairiness levels. In the event of a statistically significant main effect or interaction, a post hoc analysis was conducted using a Bonferroni correction. All data was analysed using SPSS Statistics 19 (version 28.1, Chicago, USA). Statistical significance was set at $p < 0.05$, and data were reported as means, SD and 95 % CI.

5.4 Results

Wetness Perception

There was a statistically significant interaction between hairiness and mode of application on wetness perception ($F = 6.037$, $p = 0.036$, Figure 28A). Post-hoc analyses indicated that: a) during static applications, wetness perceptions were greater under shaven vs. hairy conditions (+18.5 mm, 95 % CI: +1.5, +35.5; $p = 0.036$); and b) wetness perceptions were greater during dynamic vs. static applications under hairy conditions only (+19 mm, 95 % CI: +6, +32; $p = 0.008$). No differences in wetness perception were observed during dynamic applications between hairy vs. shaven conditions (+0.4 mm, 95 % CI: -6.2, +7.0; $p = 0.894$).

Thermal Sensation

There was no statistically significant main effect of mode of application ($F = 2.275$, $p = 0.166$), nor hairiness ($F = 4.167$, $p = 0.072$) on thermal sensation (Figure 28B); although we note that thermal sensation was coldest under static shaven conditions (62 ± 27 mm, 95 % CI: +50, +75), and the least cold under static hairy conditions (81 ± 35 mm, 95 % CI: +61, +100).

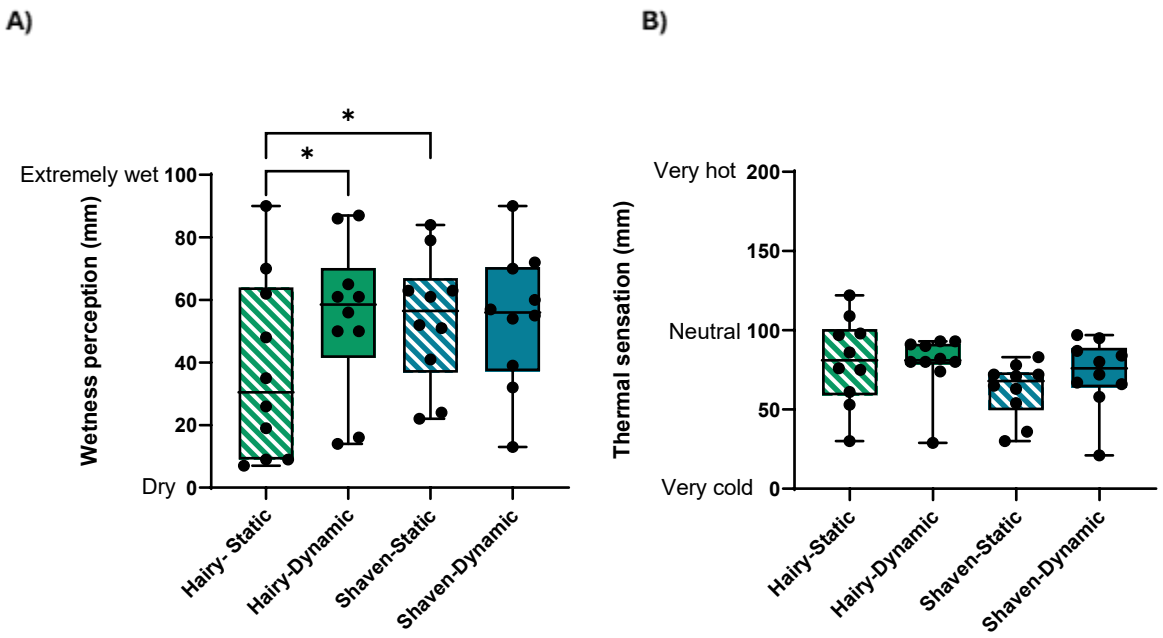

Figure 28. A) wetness perception and B) thermal sensation responses under two hairiness (hairy and shaven) and application (static and dynamic) conditions. The graphs are presented as mean and 95 % confidence interval with individual data points. *Statistical significance $p < 0.05$.

5.5 Discussion

The study aimed to investigate how the presence of hair impacts local skin wetness perception at the underarm during static and dynamic applications of cold-wet stimuli in healthy young males. We hypothesised that the presence of hairs may: 1) reduce wetness perceptions under static cold-wet applications at the underarm (i.e. insulative effect of hairs); and 2) increase wetness perceptions during dynamic cold-wet stimulations (i.e. enhanced hair-mediated tactile feedback). Our findings supported both these hypotheses.

Firstly, we observed that during static applications, wetness perception was ~20 % lower in magnitude under hairy compared to shaven skin conditions (Figure 28A). Secondly, we observed that the magnitude of wetness perception increased by ~20 % during dynamic vs. static applications under hairy conditions only. Finally, wetness perception under hairy conditions was no greater than that experienced during static or dynamic stimulation of shaven skin (Figure 28A).

Altogether, these results provide novel empirical evidence on the dual role that underarm hairs could play in modulating wetness perception, i.e. acting as “thermal insulators” under static

wet stimulus interactions, and as “perception enhancers” under dynamic wet stimulus interactions. When combined with our recent observations on the role of skin hydration levels on underarm wetness perception (Ward et al., 2025) (Chapter 4), these novel findings further expand our understanding of the thermal and tactile determinants of the “wet feel” resulting from the application of cold-wet stimuli, similar to that of APDO products at the underarm, under varying skin states (i.e. hairy vs. shaven skin).

Hair and Static Wet Stimulus Interactions

Our first observation indicated that during static cold-wet applications, wetness perception was ~20 % lower in magnitude under hairy compared to shaven skin conditions. Previous research has indicated that, when tactile cues arising from the movement of moisture across the skin are limited, individuals rely on cooling-mediated thermal cues to detect the presence of moisture on the skin (Tiest et al., 2012). Under such static wet stimulus interactions, the sensory inputs associated with the experience of wetness are primarily driven by cold sensations arising from the activation of cutaneous cold-sensitive, myelinated Aδ-nerve fibres (Campero et al., 2009), which responds to conduction- and/or evaporation-mediated skin cooling (Filingeri and Havenith, 2015). During our static cold-wet applications, the presence of hairs would have likely acted as a thermal insulator, reducing the extent of direct contact between the skin and the wet stimulus, and the resulting skin cooling. Previous evidence by Filingeri et al. (2013b), indicated that slower skin cooling rates can reduce the extent of wetness perception evoked by cold dry stimulation of the skin of the forearm, thereby reinforcing the view that modulation of local skin cooling (e.g. as likely resulting from the presence of hairs at the underarm) can alter wetness perception. A limitation of this study is that we did not measure skin temperature during the stimulation; yet, our thermal sensation data support the hypothesis of hairs acting as thermal insulators under static conditions, given that our participants reported less cold sensations under hairy dynamic vs. static stimulations (-10 mm) (albeit we note that this difference did not reach statistical significance – see Figure 28B).

It should also be noted that tactile cues are not entirely suppressed under static cold-wet applications, given that skin indentation during contact with a wet stimulus is likely to trigger mechanoreceptors in the skin (e.g. Merkel cells), which could then provide some tactile cues during static wet touch (Macefield, 2005). It appears, though, that even in the presence of such mechanical indentation, the resulting tactile cues were not of sufficient magnitude to counteract the dampening effect of hairs on those thermal cues that participants are likely to have used to rate the magnitude of wetness experience under static touch. As previously observed by Filingeri et al. (2014b) in the context of wet-stimulation of hairy skin sites (i.e. the

forearm), tactile-mediated cues seem to meaningfully increase wetness perception under dynamic wet stimulus interactions.

Hair and Dynamic Wet Stimulus Interactions

Our second observation indicated that the magnitude of wetness perception increased by ~20 % during dynamic vs. static applications under hairy conditions only. These findings are in line with previous research suggesting that the application of a dynamic stimulus increases wetness perception when compared to static wet stimulation of hairy skin (Tiest et al., 2012, Shibahara and Sato, 2019).

Whilst thermal cues may have been limited by the presence of hairs, when the stimulus was moved dynamically across the skin, it is likely that a greater activation of fast-conducting mechanoreceptors sensitive to vibration and skin friction would have occurred (Filingeri and Ackerley, 2017). Furthermore, recent evidence from microneurography studies in humans has indicated that C-tactile afferents in the skin respond to selective hair deflection (Moore et al., 2025). As C-tactile afferent activity, alongside its temperature modulation, is known to contribute to hedonic aspects of touch (Ackerley et al., 2014a), it could therefore be proposed that such hair-mediated tactile cues during dynamic wet stimulus interaction may be one of the causal factors in the observed increase in wetness perception (~20 %) from static to dynamic conditions (see Figure 28A). The potential role of hair-mediated tactile cues as “perception enhancers” for wetness is not entirely speculative. Indeed, previous research has shown that wetness perception can be increased for the same sweat level on the skin by increasing mechanical stimulation of the skin (via a clothing intervention) (Filingeri et al., 2015c). It should also be noted that some studies have highlighted that the hair could be trapping moisture, prolonging evaporative cooling and sensing air currents, which could in turn maintain and enhance local skin cooling (Liljencrantz et al., 2014, Filingeri et al., 2018). However, this effect is likely to occur post-wet contact with hairy skin, which was not addressed in the present study (i.e. perceptual outcomes were collected only during contact with wet stimuli).

While hairs may therefore be thought to enhance wetness perception under dynamic wet stimulus interactions, we should also note that wetness perceptions under dynamic hairy conditions were no greater than those experienced during dynamic stimulation of shaven skin (Figure 28A). This observation could indicate that different, yet complementary, perceptual mechanisms may lead to the same wetness perception magnitude under dynamic hairy vs. dynamic shaven conditions. In line with the previously reported neurophysiological model of wetness perception (Filingeri et al., 2014b), it would be reasonable to hypothesise that under

hairy and shaven dynamic stimulations, both thermo- and mechano-sensory cues are used to detect the perception of wetness. Yet under shaven conditions, the cooling cue is likely prevailing in driving that perception, given that the mechanical cue provided limited input (i.e. consider we did not observe a change in wetness perception from static to dynamic under shaven conditions – Figure 28A). Conversely, under hairy conditions, a suggested explanation, despite no statistical difference in thermal sensation, the limited cooling cue could be compensated by an enhanced mechanical cue during dynamic stimulation, resulting in a wetness perception magnitude equivalent to that of shaven conditions (see Figure 28A).

It should also be considered that the underarm is a rather different area of the body when it comes to hygiene routines (consider shaving and hair removal), when compared to those skin sites across the limbs and torso (e.g. forearms and fingers), which have been evaluated as part of the majority of research on wetness comparing static and dynamic interactions (Tiest et al., 2012, Raccuglia et al., 2018, Filingeri et al., 2014b, Ackerley et al., 2012). In other words, one cannot exclude that hair removal and shaving itself may have at least partly influenced the perception of wetness in our participants. Shaving for the first time and then exposing that area of the skin to a cold-wet stimulus may have increased local sensitivity due to this being a new sensory experience (Chaturvedi et al., 2024). To reduce this potential bias, repeated applications were applied to the skin to ensure test-retest reliability and reduce the bias towards an increase in wetness perception and thermal sensation during the first stimulus application. Furthermore, leaving a minimum of 24 hours after shaving before the testing session allows the biophysical changes that occur immediately after shaving on the skin of the underarm, such as increased dryness or roughness, to return to a ‘pre-shaven’ baseline (Evans et al., 2020). Nevertheless, future studies may consider investigating how both the acute and long-term effects of hair removal practices may alter local skin wetness perception. For example, long-term shaving thickens the stratum corneum, increases microvascular response and inflammatory markers, which may have a dampening effect on the receptive fields for thermal sensation, which is implicated in wetness perception (Chaturvedi et al., 2024, Turner et al., 2007).

Limitations and Experimental Considerations

Whilst the findings of this study have relevant applied implications, there are also some study limitations that are worth highlighting. For example, individual variations in the body morphology of the underarm may impact specific perceptual outcomes resulting from individual variability in contact area during both static and dynamic stimulus applications. Additionally, there could be a benefit in measuring wetness perception continuously to investigate the development and

decay in the wetness experienced during and after probe contact under all conditions. Yet, this could also provide some challenges when recording thermal sensation concurrently, as participants may prefer to move one slider more frequently than the other, depending on the verbal prompts or stimulus cues, and thus miss some of the time-dependent changes in perceptual responses. Finally, this study was only conducted on a small homogenous sample of males; therefore, it would be of benefit to repeat the test on females to observe differences or similarities in their sensitivity to temperature and wetness. It has been recorded that females are more sensitive than males to cold-wet, statically applied stimuli at various regions of the body, including the underarm (Valenza et al., 2019).

5.6 Conclusion

In conclusion, our study provides novel empirical evidence on the dual role that underarm hairs can play in modulating wetness perception, i.e. potentially acting as “thermal insulators” and reducing contact with the skin under static wet stimulus interactions, and as “perception enhancers” under dynamic wet stimulus interactions. These novel findings further expand our understanding of the thermal and tactile determinants of the “wet feel” resulting from the application of APDO products at the underarm, under varying skin states such as hairy vs. shaven skin.

Chapter 6 Experimental Study 3: A novel high-resolution methodology to assess temporal changes in skin wetness perception during and following wet stimuli contact.

Results from this chapter were under review in the peer-reviewed article below:

Ward, J., Caggiari, S., Swaile, D., Parker, K., Cochran, B., Worsley, P., Filingeri, D. (2026). A novel high-resolution methodology to assess temporal changes in skin wetness perception during and following wet stimuli contact. Behavioural Research Methods.

6.1 Abstract

Skin wetness perception arises from the integration of thermal and tactile cues, as the human skin lacks wetness receptors. Traditional methods to assess wetness perception rely on a single time-point measurement (~10 s contact), limiting insight into the temporal dynamics of wetness perception during prolonged skin-moisture interactions.

The continuous wetness perception test (c-WPT) on a digitalised 100-mm VAS (10 Hz sampling) with integrated skin temperature measurement was developed. Using a temperature-controlled hand-held stimulator, cotton patches saturated with 1 mL of fluids differing in thermal properties (water, PG, MO, PMX) were applied to the forearm of 15 healthy females for 60 seconds across five repeated applications. Participants continuously reported their wetness perception during and following contact.

Fourteen key wetness parameters were extracted from response curves and reduced via principal component analysis, and identified four main components (onset, magnitude, decay, and change after peak), explaining 75% of the variance. Test–retest reliability was good for the area under the curve and peak wetness (Intraclass correlation coefficients ≥ 0.75), and minimum detectable change thresholds were established.

The c-WPT was sensitive enough to discriminate between fluids, as such water was perceived as significantly wetter than the other fluids. The c-WPT can reliably measure the temporal dynamics of changes in wetness perception during a 60-second contact and upon the removal of a stimulus application on the forearm.

6.2 Introduction

Humans commonly experience skin wetness when their skin encounters a wet material or when it secretes sweat. This perception is learnt (Bergmann Tiest et al., 2012) as human skin lacks wetness receptors (Clark and Edholm, 1985). Extensive evidence indicates that the perception of skin wetness results from the integration of thermo-sensory cues (i.e. changes in skin temperature due to heat exchange with moisture) (Filingeri et al., 2014a, Filingeri et al., 2014c, Filingeri et al., 2015c) and mechano-sensory cues (i.e. changes in skin mechanics due to adhesion and movement of moisture on the skin) (Filingeri et al., 2015c, Ackerley et al., 2012), which are typical of skin-moisture interactions.

The experience of wetness can increase thermal discomfort (Fukazawa and Havenith, 2009), which has motivated extensive psychophysiological research on the perceptual mechanisms underlying skin wetness (Filingeri and Havenith, 2018). This has informed innovation in the design of more comfortable skin products (e.g. APDO) (Ward et al., 2025), healthcare products (e.g. absorbent pads) (Merrick et al., 2022b), and sportswear (Blount et al., 2025). Most of this empirical research has used psychophysiological approaches to investigate the relationship between stimulus properties and perceptual outcomes (Ackerley et al., 2012, Bentley, 1900, Filingeri, 2014, Shibahara and Sato, 2019). Studies commonly use QST, whereby participants are required to report their wetness perception on VAS (e.g., 100 mm with anchor points: 0 mm = dry, 100 mm = extremely wet), upon a short-duration skin contact (i.e. typically ~10 s) with a small stimulus (i.e. ~2 to 25 cm^2) varying in: a) temperature (e.g. between 2 and 20 °C below local skin temperature) (Filingeri et al., 2013b); b) moisture content (e.g. between 0 and 50mL) (Merrick et al., 2021); c) contact type (e.g. static contact or dynamically moved across the skin) (Merrick et al., 2022b, Raccuglia et al., 2018); d) skin site of application [e.g. forearm (Valenza et al., 2019), torso (Filingeri et al., 2015b), dorsal foot (Wildgoose et al., 2021) or fingertip (Feka et al., 2020)].

Results from studies have consistently highlighted the importance of changes in skin temperature in perceiving wetness (Filingeri et al., 2014b, Ackerley et al., 2012, Filingeri and Ackerley, 2017). However, psychometric evaluations of skin wetness perception have relied exclusively on a single time-point assessment, which is commonly associated with participants' first experience of wetness during contact with the stimulus, typically lasting ~10 s (Valenza et al., 2025). While relevant to our understanding of “acute” wetness perceptions, this approach offers limited insights into the temporal dynamics of wetness perceptions at the *onset* of contact, *during* a wet stimulation lasting more than ~10 s, and upon *removal* of the wet stimulus. Specifically, the current, widely used methodology does not capture the development and decay of wetness (i.e. from dry to very wet, and from very wet to dry), which is characteristic

of more realistic skin-moisture interactions. Consider for example the experience of applying a roll-on APDO on the skin of the underarm, which is likely to result in the: i) onset of wetness perceptions upon initial contact; ii) increase in wetness magnitude at a certain rate; iii) stabilisation of wetness magnitude during continuous contact (e.g. repeated roll-on); and iv) wetness decay upon loss of contact with the wet product. Within this scenario, a single time-point assessment of perceived wetness (e.g. upon initial contact) is unlikely to capture the time-dependent development of this perceptual experience in sufficient detail.

A single time-point assessment is also limited when modelling the effects of material and fluid thermal properties (e.g. thermal conductivity and heat capacity) on skin wetness perception due to the time-dependent changes in skin cooling during and following contact with a wet stimulus (Bergmann Tiest, 2015).

Extensive research on the mechanisms underlying thermal discrimination of material properties has indicated that the thermal conductivity of a material (whether solid or fluid) changes the rate of heat transfer between the skin and the material (Ho and Jones, 2006). Higher thermal conductivity can increase the rate of heat extraction from the skin, which in turn can trigger cooler sensations used for material discrimination (e.g. metal vs. wood) (Bergmann Tiest and Kappers, 2009). When fluids varying in rheology were applied to the underarm and forearm at 25 °C using different shear rates, sensory perception differed according to fluid viscosity (Guest et al., 2012). Higher viscosity fluids applied at low shear rates were perceived as colder and wetter, despite perception only being assessed at a single time point (Guest et al., 2012). The initial temperatures of the skin and the object are important factors that determine the amount of heat exchange during contact, changing the cooling curve (Ho, 2018). In wetness-related studies, skin cooling at a specific rate is known to enhance the perception of wetness (Filingeri et al., 2013b). However, little research is available on how material or fluid properties influence the perception of skin wetness, likely due to a lack of methods that can accommodate a continuous assessment of wetness perception with high temporal resolution. Furthermore, it is known that wetness perception is largely driven by skin temperature, which changes dynamically over time when in contact with a wet stimulus. Yet, current QST methods used in wetness perception research do not incorporate a continuous assessment of local skin temperature at the interface (Ackerley et al., 2012, Merrick et al., 2021, Filingeri et al., 2014b, Valenza et al., 2024). Tackling this limitation could inform a better understanding of how the temporal dynamics of changes in skin temperature drive time-dependent changes in skin wetness perception during and following contact with a wet stimulus (Ho and Jones, 2006).

To date, there are no established methodologies that assess the time-dependent changes in skin wetness perception with high resolution during and following contact with wet stimuli. The

current study aimed to address this gap, developing a reliable and sensitive method that allows continuous assessment of time-dependent changes in skin wetness perception. This approach was integrated with a continuous measurement of local skin temperature at the skin-material interface, as well as with an analytical approach to extract key features of wetness perception and its relationship with skin temperature parameters. The development of this method was described, hereby referred to as "*continuous wetness perception test (c-WPT)",* and its application in a cohort of healthy young females exposed to wet stimuli varying in heat capacity and thermal conductivity properties.

6.3 Materials and Methods

Development of the Continuous Wetness Perception Test

The development of the c-WPT was built upon previous psychophysiological research. To accommodate the continuous assessment of wetness perception for prolonged periods of time, an adapted VAS (i.e., 100 mm with anchor points: 0 mm = dry, 100 mm = extremely wet) was used. This was selected as it has been shown to be sensitive to assess local skin wetness perceptions of participants upon a short-duration skin contact (i.e. typically ~10 s) with a small stimulus (i.e. ~2 to 25 cm^2) varying in: a) temperature (e.g. between 2 and 20 °C below local skin temperature) (Filingeri et al., 2013b); b) moisture content (e.g. between 0 and 50 mL) (Merrick et al., 2021) and c) skin site of application [e.g. forearm (Valenza et al., 2019), torso (Filingeri et al., 2015b), dorsal foot (Wildgoose et al., 2021) or fingertip (Feka et al., 2020)]. Following extensive piloting (see 3.4.1), the VAS was digitalised on a 100-mm wetness perception scale using off-the-shelf data acquisition software (Daisylab, MCCDAQ, Massachusetts, USA). A moveable slider for continuous participant rating was used at a sampling frequency of 10 Hz. The VAS was displayed via a bespoke graphical user interface, which participants could freely interact with via a touchscreen whenever they experienced changes in their local wetness perception (Figure 28A).

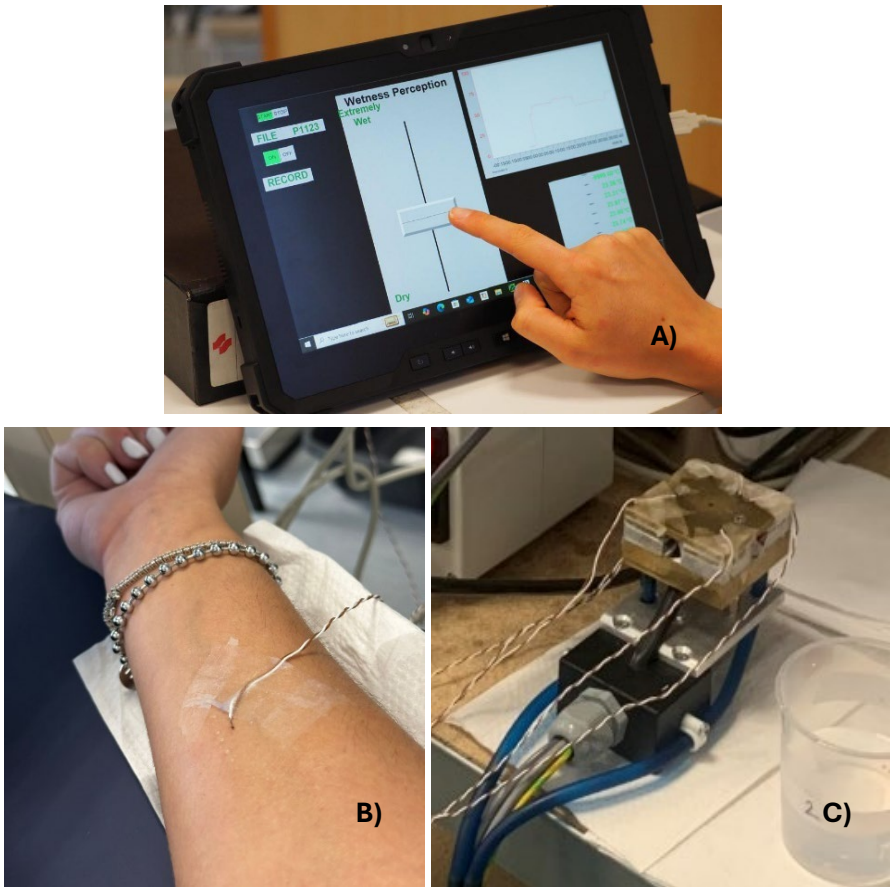

Figure 29. A) Graphical user interface displaying the visual analogue scale used to continuously assess wetness perception, with integrated skin temperature measurements recorded over time. T-type thermocouples were applied to both the skin (B) and to the surface of the stimulator (C) used to deliver (wet) stimuli onto the skin.

The data acquisition software was also used to collate concurrent measurements of temperature upon skin stimulation, using a thermocouple board with T-type thermocouple (RS Components Ltd, Coby, UK) applied to the skin (i.e. to evaluate biophysical changes in local skin temperature during the development and decay of wetness perception; Figure 29B). The thermocouples were also placed on the stimulator used to apply (wet) stimuli onto the skin (i.e. five thermocouples secured on the surface of the probe, underneath the cotton patch to be saturated with fluids, Figure 29C).

The digitalised VAS and contact thermometry allowed for the continuous assessment of wetness perception and skin-stimulus interface temperature upon contact with local wet stimuli. Such stimuli were delivered using a bespoke thermal stimulator which consisted of a temperature-controlled, hand-held device (Figure 29B), with a (square) stimulating surface of 25

cm^2, see Gordon et al. (2024) for further details. The device allows for the mounting of various textile patches at the stimulating surface, which can then be saturated with fluids to deliver wet stimuli at controlled temperatures (Figure 30).

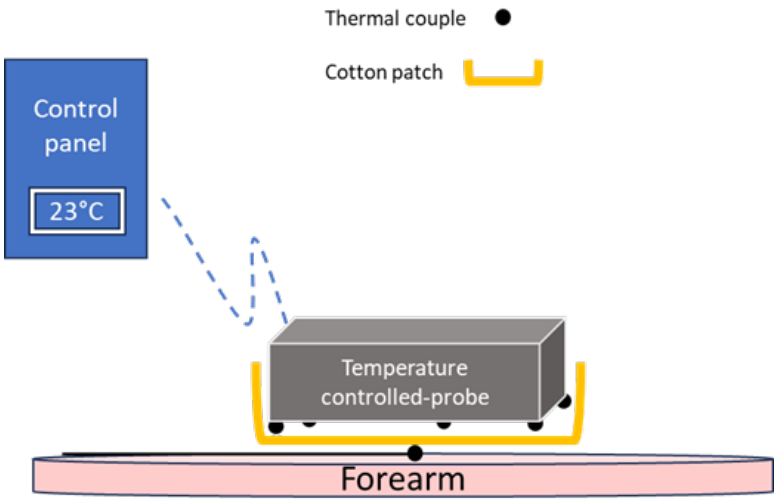

Figure 30. Schematic to demonstrate the experimental setup of a temperature-controlled, hand-held device and a mounted textile cotton patch on the forearm, with indication of thermocouples placement.

Once the hardware and software design were finalised, piloting commenced with the stimulus applications lasting 60 s, to allow the assessment of time-dependent changes in the onset and stabilisation of wetness perception over a time window that would be well beyond that commonly employed in previous studies (i.e. ~10 s). Furthermore, the evaluation included time-dependent changes in the decay of wetness perception following stimulus removal, which lasted as long as required for participants to perceive the experience of dryness. Altogether, this novel approach enabled the evaluation of the onset and decay of wetness perception with high temporal resolution, as well as its underlying biophysical correlates (i.e., time-dependent changes in skin temperature).

This stimulation approach was initially piloted in a small sample of healthy participants (N = 3), which highlighted the need for further refinements of the methodology. First, it was identified that the need to improve repeatability of individual perceptual responses by means of increasing the number of independent, repeated applications of the same wet stimulus to the skin site. It was identified that 5 repeats are an ideal number per stimulus because of the need to balance the repeatability to identify the consistency in the results of the wet stimulations,

with the potential impact of such repeated applications on changes in local SCH, local skin temperature, and the resulting skin wetness perception. To further reduce carryover effects, we also identified an ideal inter-stimulus interval of 2 minutes.

This initial piloting phase was also used to identify initial wetness perception parameters that would be considered meaningful to characterise the onset, development and decay of wetness perception during and following contact. Figure 31 presents a typical wetness perception response from an individual participant during the c-WPT piloting phase. Using this curve as a model, 14 wetness perception parameters were identified, which could be separated between the during-contact and post-contact phases (Table 4).

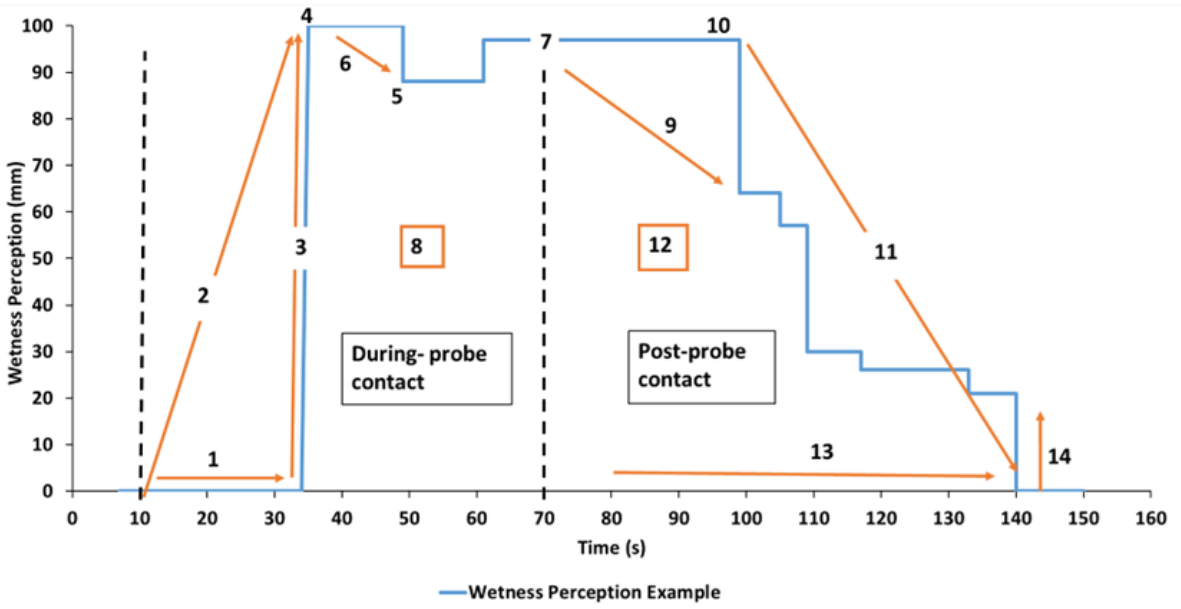

Figure 31. Presents a typical wetness perception response from an individual participant during the c-WPT pilot. Using this curve as a model, 14 wetness perception parameters were identified, which could be separated into the during-contact and post-contact phases. The orange lines and boxes refer to the 14 parameters identified and extracted from the wetness perception curve. *See Table 4 for label descriptors.*

Table 4. Description of parameters identified in the wetness perception curve, which can be separated into the probe contact and post-probe contact phases.

Parameters	Descriptions
1. Time to respond	Time between 0 start of contact and first change in WP (delta +1 mm from 0 mm) during 60 s end of contact.
2. Rate of change	The slope of the line of best fit between the time to respond to the peak in wetness perception (WP).
3. Time to peak	Time between the start of contact and the peak WP value during contact time.
4. Peak WP	Maximum WP value from the contact point (GU input) to the end of the 60 s (GU input) contact time.
5. Minimum WP	The minimum WP score following the WP peak during the 60 s contact time.
6. Delta Change	Delta change between peak WP value and min WP value during contact time.
7. End of contact time	GU input at the 60 s end of contact time and recorded WP value.
8. Area under the curve	Cumulative WP between the time to respond during contact and 60 s after the end of contact time.
9. Time to respond POST	Time between the end of contact value and first change in WP (delta -/+1 mm) post contact.
10. Peak WP POST	Peak WP value from post contact point (GU input) to the first 0 mm WP value.
11. Rate of change POST	If peak WP exceeds WP at 60 s, the slope is taken from peak post-contact to the first 0 mm WP; if equal, the slope is taken from the response time post-contact to the first 0 mm WP.
12. Area under the curve POST	Cumulative WP between the time to respond post contact and the first 0 mm WP.
13. Time to baseline POST	Time between the end of contact value and the time to the first 0 mm WP value post contact.
14. Deviation from baseline	WP value for time to baseline when 0 mm has not been reached.

Note: GU input = graphical user Interface tool which serves as a point-and-click application data input function, WP = wetness perception.

Following the development and piloting of the c-WPT, its repeatability and reliability were assessed in a cohort of healthy young females exposed to wet stimuli varying in heat capacity and thermal conductivity properties. This experiment aimed to support data generation that could inform a refined, analytical approach to extract key features of the continuous wetness perception response (e.g. minimum detectable difference amongst different stimuli) and to evaluate perceptual changes as a function of specific stimulus properties (e.g. heat capacity and thermal conductivity).

Experimental Evaluation of the c-WPT in a Cohort of Healthy Young Females

The study was a randomised, single-blind crossover design to evaluate the c-WPT in a cohort of healthy volunteers. Fifteen non-smoking, physically active females (28 ± 5 y; 1.68 ± 0.06 cm; 64.8 ± 0.3 kg; 23 ± 2.5 kg/m^2) participated in the study. The volunteers had no history of sensory-related disorders or cardiovascular, neurological, or skin-related conditions (e.g., eczema). While empirical evidence on this topic remains limited, it is acknowledged that hormonal fluctuations associated with the menstrual cycle could have impacted local sensory responses. As such, the participants' self-reports of the specific day of their most recent menstrual cycle were gathered. This study was approved by the University of Southampton Ethics Committee (no.81776). All participants provided written informed consent before testing. The study conformed to the ethical standards set by the Declaration of Helsinki.

Experimental Procedures

To mitigate expectation bias, all participants were blinded to the nature of the stimuli (e.g. type and temperature of fluids to be applied on the skin), and they were provided with information solely regarding the location of the stimulation and characteristics of the c-WPT (i.e. requirement to continuously rate their local wetness perception as and when it differed to and from baseline). All participants undertook a familiarisation session, followed by one testing session performed in a thermoneutral environment (ambient temperature: 25 °C; relative humidity: 45 %).

During the testing session, participants were required to continuously report their ongoing wetness perceptions on the VAS slider (Figure 29A) during the application of cold-wet stimuli (stimulator temperature: 23 °C) varying in fluid content during and following 60-second static contact. The stimulator was applied to the volar surface of the right forearm (i.e., the midpoint between wrist and antecubital fossa, Figure 29B). Application force was measured with an

integrated load cell onto the thermal stimulator and maintained at a minimum (i.e. < 1 N) to ensure full contact without pronounced indentation.

To assess whether the c-WPT was sensitive to detect changes in fluid interactions, four different liquids were selected to be applied onto the skin, i.e. water, PG, MO, and PMX. These fluids have a range of heat capacity and thermal conductivity properties (Table 5) that are known to induce different perceptions of wetness even when applied at the same volume and temperature onto the skin (Bergmann Tiest, 2015). All fluids were non-toxic, colourless, and odourless, and they were all applied at the same temperature (i.e., 23 °C), and in the same volume (1 mL). To deliver a controlled application of those fluids onto the skin, 100 % cotton patches were saturated with 1 mL of each fluid, secured onto the probe, and delivered at the given application pressure (i.e. < 1 N) onto the skin. In a randomised sequence, each fluid was applied to the forearm five times, with two minutes in between applications, giving a total of 20 repeated measures per participant.

Table 5. Fluids' heat capacity and thermal conductivity properties.

Fluid	Thermal conductivity (W/m·K)	Heat capacity (J/g·C)
Water	0.598	4.18
PG	0.206	2.49
PMX	0.153	1.52
MO	0.136	1.67

Upon application of a wet stimulus, participants were encouraged to continuously report the magnitude of their wetness perception during both contact (initial 60 s) and the subsequent post-contact phase.

Alongside perceptual assessments, biophysical changes in local skin temperature were continuously monitored using thermocouples on the forearm (Figure 29A), and on the surface of the probe below the saturated cotton patches (Figure 29B).

By standardising the application temperature (i.e. 23 °C) and pressure (< 1 N), contact time (60 s), and fluid volume (i.e. 1 mL), the experimental design was used to identify the independent effects of fluids' thermal properties on continuous wetness perception responses with a high temporal resolution.

Analytical Approach to Data Extraction and Analysis

The analytical approach to data extraction and analysis consisted of four phases: i.e. 1) Parameter extraction; 2) Principal component analysis (PCA); 3) Calculation of reliability (intraclass correlation coefficients) and minimum detectable change (MDC); 4) Analysis of the effect of fluids on selected parameters.

Phase 1- Parameter Extraction

As noted earlier, the piloting phase was used to identify 14 wetness perception parameters that were considered meaningful to characterise the onset, development and decay of wetness perception during-contact and post-contact phases (Table 4). To identify and extract these 14 parameters in each of 300 separate data files recorded during testing of the 15 female participants (i.e. each receiving 5 repeated applications of 4 different fluids), a custom MATLAB script (Mathworks, USA) was developed. As a result, 15 independent datasets (i.e. 1 for each participant) were produced, each consisting of an average value (i.e. from the 5 repeats) of each wetness perception parameter.

Phase 2- Principal Component Analysis

PCA was used on the wetness perception dataset to evaluate cross-correlation between parameters, reduce complexity in the dataset, and identify key features of the wetness perception response during and post-contact. The PCA approach focused on identifying principal components (PC), which would collectively explain a minimum of 70% of the variance in wetness perception. Once the PC were identified, key wetness perception parameters within each PC were selected as representative features to be used for further analysis.

Phase 3- Calculation of Minimum Detectable Change

Intraclass correlation coefficients (ICC) were calculated for the selected wetness perception parameters within each PC, using a two-way mixed model with absolute measures (2, k), to evaluate test-retest reliability. ICCs were interpreted as follows (Portney & Watkins, 2000):

- below 0.50: poor
- between 0.50 and 0.75: moderate
- between 0.75 and 0.90: good
- above 0.90: excellent

Standard error of measurement was then calculated [SEM = SD x $\sqrt{}$(1 – ICC), where SD is the standard deviation]. Finally, SEM values were used to quantify the MDC for each parameter as per the following formula, i.e. MDC = SEM x 1.96 x $\sqrt{}$2. The MDC can be interpreted as the smallest amount of change in a measured variable that can be confidently detected as a real change, rather than being due to measurement error.

Phase 4- Analysis of the Effect of Fluids on Selected Parameters

The selected wetness perception parameters arising from the PCA were assessed for normality and homoscedasticity using the Shapiro–Wilk and Levene tests, respectively. To determine the effect of fluid on wetness perception, the parameters were analysed for the independent effect of fluid (four levels: water, PG, MO, PMX) and repeat (five levels: 1 - 5) by means of either a two-way repeated measure ANOVA (i.e. for normally distributed data, with Tukey's post hoc analysis) or a Friedman test (i.e. for non-normally distributed data, with Wilcoxon signed-rank post-hoc analysis). Statistical significance was set at $p < 0.05$, and data were reported as means, SD and 95 % CI. All data were analysed using SPSS Statistics 19 (version 28.1, Chicago, USA).

6.4 Results

Quantitative evaluation of wetness perception and skin temperature responses clearly highlighted characteristic response profiles (Figure 32).

Regarding the c-WPT curves, the following observations were made; i) a time-dependent onset following contact with the wet stimulus; ii) progressed to a peak magnitude; iii) declined slightly towards the end of contact; and iv) decayed following stimulus removal. Differences in the magnitude of perceived wetness could be observed amongst fluid applications, albeit all shared similar profiles. The duration of the post-contact phase was on average 41 s (± 9 s), which is the average time participants took to (re-)experience dryness (i.e. slider in "0" position on VAS, Figure 28A) post stimulation.

Regarding skin temperature, relative changes presented a characteristic Newtonian cooling profile (Newton, 1809) during contact, which was characterised by i) an initial, pronounced decrease upon immediate contact with the wet stimulus; ii) a further, albeit slower, decrease during continuous contact. Following stimulus removal, skin temperature was then observed to rise towards baseline levels. Differences in the magnitude of skin cooling could be observed

amongst fluid applications, with water resulting in the largest drop in skin temperature during contact (2.6 ± 0.9 °C), followed by PG (2.2 ± 1.1 °C), PMX (2.1 ± 0.8 °C), and MO (1.8 ± 1.0 °C).

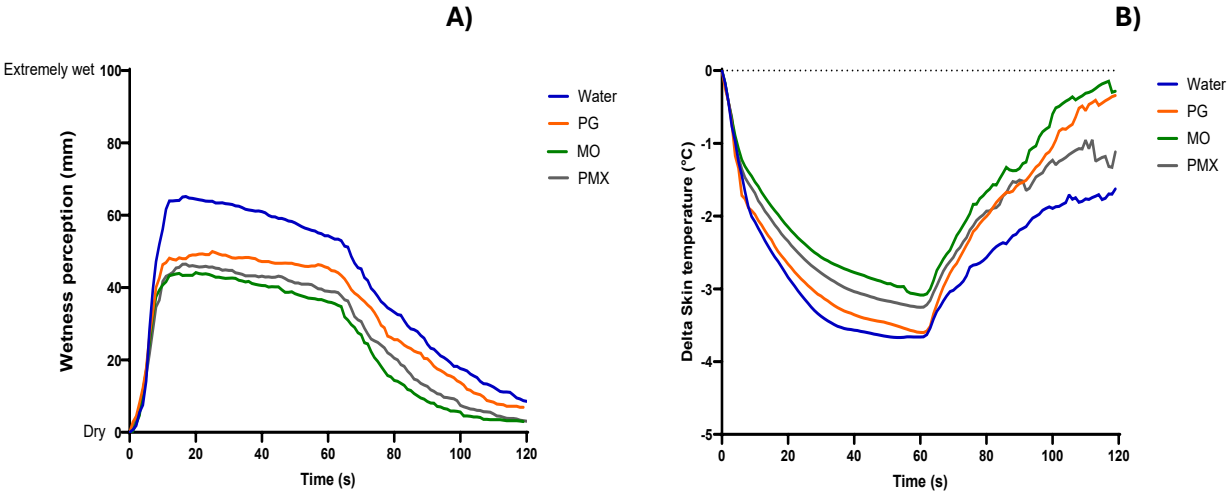

Figure 32. Presents continuous mean wetness perception (N = 15, panel A) and delta skin temperature (N = 15, panel B) responses during both contact and post-contact phases of the c-WPT, and in relation to each of the four fluids used.

Parameter Extraction and Principal Component Analysis

The PCA indicated that 75 % of the variance in wetness perception could be described by the first 4 PC. Specifically, 39.5 % of the variance was explained by PC 1; 15.7 % by PC 2; 11.4 % by PC 3 and 7.9 % by PC 4. The characteristics of the parameters within each PC (Table 6) led us to consider PC 1 as representative of the "magnitude of wetness perception"; PC 2 as representative of the "decay of wetness perception"; PC 3 as representative of the "onset of wetness perception"; and PC 4 as representative of "change in wetness perception following peak".

Table 6. The four PCs identified explained 75% of the variance in wetness perception, with associated parameters within each PC and related correlation coefficients.

Wetness perception								
Parameter	**Magnitude of wetness perception**		**Decay of wetness perception**		**Onset of wetness perception**		**Change in wetness perception following peak**	
	PC	**Correlation coefficient**	**PC**	**Correlation coefficient**	**PC**	**Correlation coefficient**	**PC**	**Correlation coefficient**
Peak	1	0.92						
Minimum	1	0.95						
EoC	1	0.95						
Delta							4	0.70
T2R					3	0.70		
T2P					3	0.68		
RoC								
AUC	1	0.97						
Peak Post	1	0.96						
T2R Post			2	0.87				
T2B Post			2	0.81				
RoC Post								
AUC Post	1	0.51	2	0.78				
Deviation Baseline							4	0.68

Note: EoC = End of contact; T2R = Time to respond; T2P = Time to peak; RoC = Rate of change; AUC = Area under the curve; T2R Post = Time to respond post contact; T2B Post = Time to baseline post contact; RoC post = Rate of change post contact; AUC post= Area under the curve post contact.

Based on the outputs of the PCA (Table 6), parameters with the highest correlation coefficient within each PC were identified and selected for further analysis. These parameters consisted of area under the curve (AUC), time to respond post contact (T2R post), time to respond during contact (T2R), and change in wetness perception between peak and lowest wetness (delta), for PC 1, 2, 3 and 4, respectively. Peak wetness during contact (peak) within PC 1 was also selected for further analysis because it was the only parameter that could be indicative of the "acute" wetness perception commonly reported in previous studies that investigated wetness during the initial contact with a wet stimulus lasting ~10 s.

Minimum Detectable Change

The parameters of AUC, peak, T2R post, T2R, and delta, were used to assess the reliability and MDC (Table 7).

Test-retest reliability was good for AUC and peak wetness (i.e. ICC ≥ 0.75); moderate for T2R and delta (i.e. 0.50 < ICC < 0.75); and low for T2R post (i.e. ICC < 0.50).

MDCs for each parameter (Table 7) were calculated to inform the interpretation of differences in wetness perception in relation to fluid application.

Table 7. Mean [with standard deviation (SD)], ICC [with 95% Confidence interval (CI)], SEM, and MDC values for area under the curve (AUC), peak wetness during contact (peak), time to respond post contact (T2R post), time to respond during contact (T2R), and difference between peak and lowest wetness (delta).

Principal Component	**1**	**1**	**2**	**3**	**4**
Parameter	**AUC (mm^2)**	**Peak (mm)**	**T2R post (s)**	**T2R (s)**	**Delta (mm)**
Mean (SD)	2657 (488)	55 (9)	11 (0.7)	6 (0.9)	12 (1)
ICC	0.89	0.88	0.13	0.42	0.56
ICC CI	0.83 0.93	0.83 0.93	-0.30 +0.45	0.14 0.63	0.36 0.72
SEM	169	315.7	0.65	0.70	0.85
MDC	467	8.23	1.80	1.93	2.3

Analysis of the Effect of Fluids on Selected Parameters

Area Under the Curve

There was a statistically significant main effect of fluid ($F_{(3, 30)}$, = 18.716, $p < 0.001$), but no effect of repeat ($F_{(4, 40)}$, = 0.613, $p = 0.656$) nor interaction effect ($F_{(12, 120)}$, = 0.623, $p = 0.820$) on the AUC (Figure 33A). Post hoc analyses revealed a significantly greater AUC for wetness perception during contact with water compared to MO (+1143 mm^2, 95 % CI: +403, +1882, $p = 0.003$), PMX (+919 mm^2, 95 % CI: +248, +1591, $p = 0.007$), and PG (+846 mm^2, 95 % CI: +215, +1478, $p = 0.008$). The differences in AUC for wetness perception between water and all other fluids were,

on average, twice as large as the MDC for this parameter (see Table 7). Hence, this difference is to be considered a meaningful difference beyond measurement error.

Peak Wetness Perception

There was a statistically significant main effect of fluid ($F_{(3, 30)} = 19.35$, $p < 0.001$), but no effect of repeat ($F_{(4, 40)} = 1.55$, $p = 0.205$), nor interaction effect ($F_{(12, 120)} = 0.392$, $p = 0.964$) on peak wetness perception (Figure 33B). Post hoc analyses indicated that participants reported a higher peak wetness perception during contact with water compared to MO (+20 mm, 95% CI: +7, +34; $p = 0.003$), PMX (+17 mm, 95% CI: +5, +29; $p = 0.007$), and PG (+13 mm, 95% CI: +2, +25; $p = 0.015$). Higher peak wetness perceptions were also reported during contact with PG compared to MO (+7 mm, 95 % CI: +1, +12; $p = 0.018$). The differences in peak wetness perception between water and all other fluids were, on average, twice as large as the MDC for this parameter (see Table 7). Hence, this difference in peak wetness perceptions between water and the other 3 fluids was meaningful beyond measurement error.

Time to Respond During Contact

There was no statistically significant main effect of fluid ($F_{(3, 30)} = 0.236$, $p = 0.746$), repeat ($F_{(4, 40)} = 1.091$, $p = 0.374$), nor interaction effect ($F_{(12, 120)} = 1.027$, $p = 0.429$) on T2R during contact with the wet stimuli (Figure 33C). The corresponding average (± SD) T2R for each fluid was: PG (6.3 ± 0.4 s), MO (5.8 ± 0.4 s), water (5.7 ± 0.6 s), and PMX (5.7 ± 1.1 s). When the T2R was averaged for all the repeats, participants and fluids, the participants took ~ 6 ± 0.5 s to respond to a wet stimulus being applied to the skin, regardless of the fluid.

Time to Respond POST Contact

Regarding T2R post data, there was no statistically significant effect of fluid nor repeat for the T2R to the stimulus being removed from the skin (Chi square = 22.840, $p = 0.244$, Figure 33D). The corresponding average (± SD) T2R for each fluid was: PG (12.2 ± 10.3 s), water (11.2 ± 13.1 s), MO (10.7 ± 9.3 s), and PMX (10.6 ± 10.9 s). When the T2R was averaged for all the repeats, participants and fluids, the participants took ~ 11 ± 0.7 s to respond to a wet stimulus being removed from the skin, regardless of the fluid.

Changes in Wetness Perception Between Peak and Lowest Wetness

There was no statistically significant effect of fluid nor repeat (Chi square = 25.348, $p = 0.149$) for the change in wetness perception between peak and lowest wetness (Figure 33E). The delta values for each fluid were water (13 ± 12 mm), MO (12 ± 14 mm), PMX (12 ± 13 mm) and PG (10 ± 10 mm). These observations indicated that changes in wetness perception between peak and lowest values during contact were relatively modest and that they did not differ among fluids.

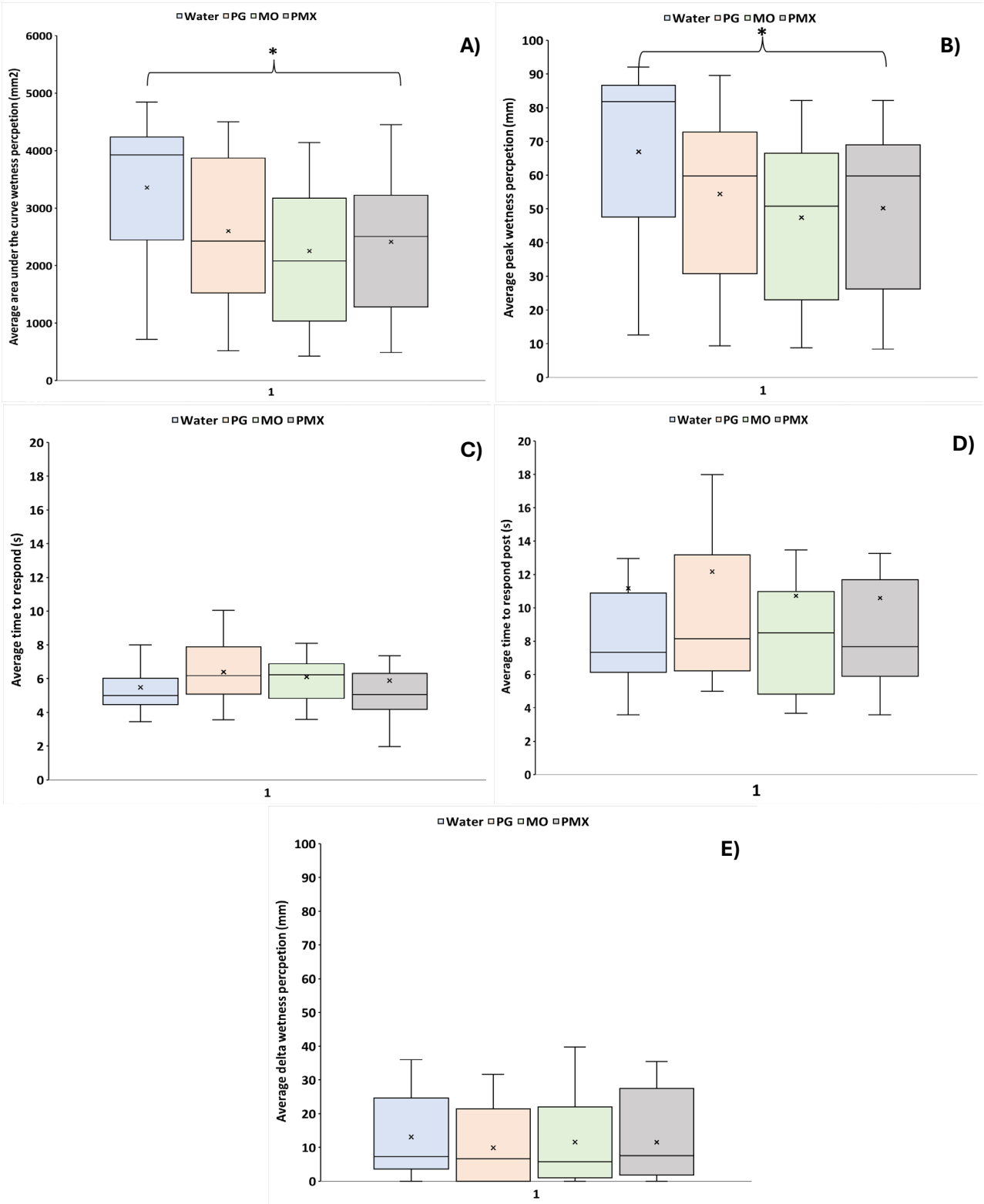

Figure 33. Representing the wetness perception data for each parameter: A) area under the curve, B) peak wetness perception, C) time to respond, D) time to respond post contact, E) delta change in wetness. Separated by the four fluids: water, propylene glycol (PG), mineral oil (MO), and dimethicone (PMX). Presented as mean, standard deviation, minimum, maximum and interquartile range. *Statistical significance $p < 0.05$.

6.5 Discussion

The study presented a novel methodology to assess time-dependent changes in skin wetness perception with high resolution during and following contact with wet stimuli. The approach appeared feasible to perform psychophysiological experiments on the perceptual experience and associated biophysical changes resulting from the skin's contact with a wet stimulus. The method was indeed sensitive in identifying wetness perception differences resulting from the skin's contact with fluids of varying thermal properties (see Figure 31), such as fluids used in the chemical formulation of APDO products. This extends our knowledge beyond the simple application of water onto the skin, which, although relevant for many scenarios, is not always fully representative of complex fluid formulations, such as those found in APDO product application or sweat accumulation on the skin (Gerrett et al., 2013, West et al., 2019). The method was also effective in characterising the time-dependent differences in skin cooling profiles likely underlying the observed perceptual differences across fluids, i.e. whereby the faster and greater the skin cooling (e.g. in the case of water – see Figure 32), the greater the magnitude of wetness experienced across the whole contact phase. This can help better our understanding of the relationship between decreases in skin temperature and changes in wetness perception throughout and following stimulus application (Valenza et al., 2019).

The development and assessment of the c-WPT have highlighted the importance of continuously measuring wetness perception with integrated skin temperature. By capturing 14 parameters during the development and decay of wetness upon stimulus application and removal, the approach provided greater insights into time-dependent scenario-specific skin-moisture interactions. This addresses a current methodological limitation, whereby previous studies have relied on a single time-point assessment of wetness perception (Wildgoose et al., 2021, Ackerley et al., 2012, Valenza et al., 2023, Filingeri et al., 2014a). In comparison to our understanding of 'acute' wetness perception through previous studies, the novel method goes beyond previous single time-point assessments by revealing four key phases in the temporal dynamics of local wetness perception, namely the *'onset of wetness', the 'magnitude of wetness', the 'decay in wetness' and the 'changes in wetness after peak'*.

Certain parameters analysed in the PCA highlight further limitations to the previous method for assessing wetness. Consider, for example, the parameter '*T2R during contact*': these results indicated that participants took ~6 s to respond (i.e. moved the sliding scale) once the stimuli were applied onto the skin, regardless of the fluid applied. Yet, their first perceptual response did not coincide with reaching their peak wetness perception, which occurred later during contact (~15 to 20 s, see Figure 32). It therefore follows that the magnitude of perceived wetness develops over a longer timeframe than previously addressed (i.e. ~10 s) and it is characterised

by an initial response that precedes a peak response. A 10 s single-time point assessment of wetness may therefore be insufficient to detect meaningful differences in the peak perceived wetness resulting from different fluid interactions. Similar methodological issues were previously seen in the study of pain that used a thermal temporal summation, whereby a single pain rating at the end of a heat pulse was not adequate in capturing precise measurements during stimulus administration (Kong et al., 2019). This has since led to the development of continuous pain rating VAS, which allows the collection of perceptual data with higher temporal resolution and key parameter extraction (Kong et al., 2019).

It is also important to note that, despite no differences in the participants' T2R, there were statistically significant differences in peak wetness between water and the other three fluids, and between PG compared to MO. These differences appear to be well described by the heat capacity and thermal conductivity properties of the tested fluids. Specifically, water presented much higher heat capacity than all other fluids, and PG had slightly greater heat capacity than MO (Table 5). Conversely, thermal conductivity was higher for water only, with the remaining fluids all presenting similar thermal conductivity (Table 5). Previous material discrimination studies had indicated that the rate of heat transfer plays a significant role in thermal and touch discrimination of liquids and solids (Bergmann Tiest, 2015, Jones and Berris, 2003, Ho and Jones, 2006), and that it could also be driving the characterisation of a stimulus as cold or wet (Filingeri et al., 2013a); yet until now, limited evidence was available on the extent to which meaningful differences in fluid's thermal properties (e.g. consider water vs. MO) would translate into perceptual differences in wetness (Jones and Berris, 2003, Ho, 2018, Guest et al., 2012). The current method appears sensitive to detect such physical differences and their perceptual correlates in relation to the experience of wetness upon contact with fluids, as also evidenced by the skin cooling profiles presented in Figure 32 which mirror the wetness perception responses.

It is well established that materials with higher heat capacity and thermal conductivity extract heat at a faster rate and are often perceived as colder (Bergmann Tiest and Kappers, 2009). This may underlie the observation that water is being perceived as wetter than other fluids, as previous research has revealed that the activation of the thermoreceptors, through cooling the skin, represents the primary inducer of wetness perception (Filingeri et al., 2013b). It therefore remains to be established to what extent thermal signals may interact with mechanical fluid properties (e.g. viscosity) in driving fluid-dependent differences in wetness perception (Guest et al., 2012). The skin temperature cooling curve (Figure 32), followed a similar trace to that seen during skin-material interaction (Havenith et al., 1992, Bergmann Tiest and Kappers, 2009, Ho, 2018). Whereby, the first phase comprises of a rapid initial drop in skin temperature at the moment of contact, followed by the second phase, a slower change in skin temperature with

prolonged contact, known as the total change in skin temperature during the contact period (Havenith et al., 1992). This cooling curve is often modelled as a Newtonian cooling curve, initially used to model the cooling of a solid inorganic body to the temperature of the environment (Newton, 1809). It has been identified that for materials with a high contact coefficient, such as metals, the cooling process is overall quicker and dominated by the initial higher cooling phase, and therefore, results in a larger total change in skin temperature. Whereas, with materials having a smaller contact coefficient, such as foam, the cooling process is relatively slow, and both the initial and second phases are longer, with the second phase dominating the overall cooling process (Ho, 2018). The contact coefficient represents the material's ability to conduct, store and extract heat from the skin, which is directly linked to the degree of coldness perceived when touching an object (Havenith et al., 1992). This is a product of the thermal conductivity and heat capacity of the material (Mills, 1999). Therefore, it might be concluded that during fluid-skin interactions, the contact coefficients impact the cooling curves, resulting in a larger total change in skin cooling with water, which has a higher contact coefficient due to its greater thermal conductivity and heat capacity (Table 5), and a slower reduction in skin cooling with MO, the fluid with the smallest contact coefficient.

Independent of fluid discrimination, the current method also appears sensitive to characterise time-dependent changes in wetness perception. The PCA was conducted to explore the underlying structure of the dataset and reduce dimensionality whilst preserving the maximum variance (Chen et al., 2024). The PCA highlighted that 75 % of the variance in the wetness perception curve can be accounted for by the four principal components, *'onset of wetness', 'magnitude of wetness', 'decay in wetness' and 'changes in wetness after peak'*. Moreover, the ICC assessed test-retest and inter-rater reliability for wetness perception across the repeated measurements and four fluids. The ICC for the selected parameters of AUC, peak wetness, T2R post, T2R during contact and delta change was 0.89, 0.88, 0.13, 0.42, and 0.56, respectively, indicating a range of parameter reliability. To our knowledge, no studies have examined the reliability or the MDC for wetness perception until now. Despite co-variance in some parameters, there is low reliability within certain parameters, such as T2R post contact. This might provide some limitations to the post-contact data, which needs to be considered, specifically the 'decay in wetness' component. Yet, the low reliability may stem from the variability in individual responses to the removal of the stimulus, which lasted as long as required for participants to perceive the experience of dryness. During the analysis, it was highlighted that in the first repeat of each stimulus application, participants reported a greater sensation of wetness than in the additional four repeats, irrespective of fluid. This could skew the data; however, when assessing the ICC without the first repeat, the reliability values did not change. Thus, it might be a consideration when planning to use a method where the application

of the stimuli is only applied to the skin once, as this might represent an elevated wetness value. The c-WPT has shown it is also sensitive enough to discriminate differences within specific parameters between the fluids. For the first time, wetness perception parameters have a set threshold for an MDC. Here, it demonstrated the sensitivity of the 100 mm VAS for both the previous studies and the current method. This provides confidence in our understanding in that the difference in wetness responses to various stimuli now has a known measurement error, therefore ensuring changes outside of this range are meaningful differences beyond mere noise.

Finally, it would be a question for the investigator whether their perceptual and biophysical measure requires a high-resolution temporal dynamic measurement to assess changes in wetness perception over time, or if a one-timepoint short duration 'acute' measurement of wetness is sufficient to understand their methodological question. For example, if the researcher wanted to understand how fluids varying in their thermal properties, such as those in the chemical formulation of APDO, when blended, impact wetness perception and changes in corresponding skin temperature for a prolonged duration of time, then the new c-WPT method would be preferred. However, if the research question was to identify how the initial experience of a wet stimulus felt on a region of the skin during a short ~10 s contact, then a one-time 'acute' measurement of wetness may be more relevant. Neither method should be considered the only option when assessing wetness perception. The research question at hand, the aims of the study, and the hypothesis should guide the methodological development to find the most relevant assessment for wetness perception.

6.6 Conclusion

The study concludes that the newly developed c-WPT can reliably measure the temporal dynamics of changes in wetness perception during a 60-second contact and upon the removal of a stimulus application on the forearm. Additionally, this method provides integrated biophysical skin temperature measures and perceptual responses for wetness during stimulus interaction, enhancing our understanding of the relationship between the two during the development and decay of the wetness experienced on the skin. Furthermore, meaningful characteristics (i.e. onset, magnitude and decay) and parameters (i.e. peak wetness and AUC) were highlighted from the wetness perception and analysed for their test-retest reliability. Finally, it assessed the discriminative ability of the method through the assessment of fluids with varying thermal properties to detect skin temperature-driven time-dependent changes in skin wetness perception during and following contact with a wet stimulus, through repeated applications on the forearm. Future studies should apply this continuous assessment method to other regions of the body and with additional fluids with varying properties to provide further

understanding of the dynamic temporal interaction of wetness perception and skin temperature during prolonged contact with a stimuli

Chapter 7 Experimental Study 4: Time-dependent changes in skin wetness perception at the underarm during contact with fluids varying in thermal properties.

7.1 Abstract

APDO reduce sweating, yet users may still perceive wetness during and after application. Fluid composition influences thermal conductivity and, consequently, skin cooling upon contact, an established driver of wetness perception. However, the relationship between fluid thermal properties and underarm wetness perception remains unclear. This study investigated how fluids with differing thermal conductivities affect skin cooling and perceived wetness at the underarm.

Fifteen healthy women completed two identical QST sessions. During each session, participants continuously rated wetness (0 – 100 mm VAS: dry to extremely wet) during and immediately after 60 s contact with cotton patches (25 cm^2) saturated with 1 mL of water, PG, MO, or PMX (10 repeats per fluid). Patches were applied using a temperature-controlled probe (23 °C) with integrated skin temperature measurement.

There was a significant main effect of fluid ($p < 0.001$) and repeat ($p < 0.05$) on peak wetness perception, with no interaction. Water elicited greater wetness than MO (+22 mm) and PMX (+23 mm; $p < 0.01$). Skin cooling during contact showed significant effects of fluid ($p = 0.002$), repeat ($p < 0.001$), and interaction ($p = 0.038$). Mean skin temperature reductions were greatest for water (3.4 ± 0.4 °C), followed by PG (3.0 ± 0.7 °C), PMX (2.7 ± 0.7 °C), and MO (2.6 ± 0.7 °C).

Given the same moisture volume and temperature, fluids with greater thermal conductivity (i.e. water) produced greater skin cooling and wetness perception, informing future APDO formulation design for improved thermal comfort upon application.

7.2 Introduction

APDO are well-established hygiene products, which are applied by millions of consumers worldwide to minimise sweat-induced wetness and related malodour at the underarm (Watkinson et al., 2007). Yet, the common experience of wetness at the underarm can still occur during APDO use, including the initial contact of the skin with a “wet” APDO during product application. Experiencing wetness on the skin, through contact with fluids (e.g. a wet APDO product), has been shown to induce discomfort (Gagge, 1937, Filingeri and Havenith, 2018). Hence, a better understanding of the perceptual mechanisms underlying wetness perception at the underarm could help inform APDO design that minimises discomfort during product application.

APDO have many physical forms, such as roll-ons, aerosols, sticks and gels (Benohanian, 2001), and chemical formulations, including a mixture of fluids with different thermal conductivity and heat capacity. Studies on material discrimination have repeatedly shown that the thermal properties of the material (whether solid or fluid) influence the heat exchange between the skin and the material upon initial contact (Ho and Jones, 2006). For example, materials at the same temperature, but with higher thermal conductivity and heat capacity (consider e.g. metal vs. wood), create a larger avenue for heat exchange, which results in faster cooling and cooler sensations upon contact with the skin (Wang et al., 2023, Bergmann Tiest and Kappers, 2009).

The rate of heat transfer upon contact with a wet material, and the associated rate of skin cooling, has been previously shown to play a key role in driving skin wetness perception (Filingeri et al., 2013b, Bergmann Tiest and Kappers, 2009, Merrick et al., 2022b, Filingeri et al., 2014b). Substantial psychophysiological research has indeed indicated that, owing to a lack of wetness-sensing receptors (Clark and Edholm, 1985), humans have learnt to perceive wetness (Bergmann Tiest et al., 2012) through the integration of thermo-sensory (i.e. changes in skin temperature due to heat exchange with moisture) (Filingeri et al., 2014a, Filingeri et al., 2014c, Filingeri et al., 2015c) and mechano-sensory cues (i.e. changes in skin mechanics due to adhesion and movement of moisture on the skin) (Filingeri et al., 2015c, Ackerley et al., 2012), which are typical of skin-moisture interactions. Yet, this research has traditionally relied on an acute single-time point measurement of wetness perception. Limiting our understanding to the initial response or first experience of wetness, rather than the widely used continuous psychophysics method seen in pain research (Marcuzzi et al., 2017, Campolo et al., 2022, Burge and Bonnen, 2025), for tracking the development and decay in perception, which is more likely a realistic skin interaction scenario.

Consider the application of APDO products, it could trigger an unwanted perception of wetness, particularly when a “wet” product at room temperature (~23 °C) contacts the skin of the underarm (typically ≥ 34 °C). This application could likely result in a series of temporal wetness perception “events”: i) onset of wetness during initial contact between the skin and the product; ii) increase in wetness over time and at a certain rate; iii) fluctuations of the magnitude in wetness during continuous contact (e.g. recurring action); iv) wetness decay upon removal of the stimulus (Chapter 6).

The time-dependent changes in perceived wetness described above were recently demonstrated (Chapter 6) as part of the development of a novel methodology (i.e. c-WPT) to evaluate dynamically changing perceptions upon prolonged wet stimulus contact with the skin (~60 s). Specifically, using the forearm as a representative skin site, applying this novel method and identifying four key phases in the experience of wetness upon contact and removal of a wet stimulus, namely the *‘onset of wetness’, the ‘magnitude of wetness’, the ‘decay in wetness’ and ‘changes in wetness after peak’*. Importantly, the method was sensitive to detect perceptual differences (e.g. in AUC and peak wetness perception) resulting from the application of fluids with higher thermal conductivity.

However, the impact of the thermal properties of the fluids contained in APDO on wetness perceptions remains poorly understood, particularly during stimulation of a skin site such as the underarm, a unique region of the human body. This highlights the need to investigate how thermal properties, and in particular the thermal conductivity and heat capacity of fluids in APDO’s chemical formulation, impact wetness perception using a temporal evaluation. This knowledge can inform innovation in the design of products that feel more comfortable during application.

Therefore, the current study aimed to apply this novel methodology to the investigation of wetness perception at the underarm, during and following contact with wet stimuli presenting a range of thermal conductivity and heat capacity properties alike those encountered in APDO formulations. Specifically, we selected fluids commonly contained in APDO formulations, i.e., PG and PMX, alongside control fluids with widely expected perceptual behaviours, such as water and MO, and we applied them to the skin of the underarm in a cohort of healthy young females.

7.3 Materials and Methods

The testing procedures were explained to all volunteers, who gave written informed consent prior to participation. The University of Southampton Ethical Committee approved the research study (no. 81776). All procedures were conducted in accordance with the principles outlined in the Declaration of Helsinki.

Participants

Fifteen non-smoking, physically active females (28 ± 5 y; 1.68 ± 0.06 cm; 64.8 ± 0.3 kg; 23 ± 2.5 kg/m^2) who regularly remove their underarm hair were recruited for a randomised single-blind crossover study. Priori sample size calculation was performed using an effect size corresponding to f = 0.71 (Filingeri et al., 2013b), combined with an α = 0.05 and a β (power) = 0.8, which determined a minimum sample of fourteen participants. Fifteen participants were recruited in case of loss to follow-up.

The volunteers had no history of sensory-related disorders or cardiovascular, neurological, or skin-related conditions (e.g., eczema). In preparation, participants refrained from applying APDO and were required to shave their underarm hair 24 hours before testing. While empirical evidence on this topic remains limited, we acknowledged that hormonal fluctuations associated with the menstrual cycle could have impacted local sensory responses. As such, we gathered participants' self-reports of the specific day of their most recent menstrual cycle and contraceptive use (n = 1 ring; n = 2 combined pill; n = 1 coil; n = 1 implant). Female participants were recruited for the standardisation of their hair removal process, which required them to remove their underarm hair via shaving ≥ 1 x per week. Frequent hair removal, specifically shaving, can impact SCH and epidermal thickness, which could lead to changes in sensitivity (Turner et al., 2007, Verrillo et al., 1998, Chaturvedi et al., 2024).

Experimental Design

All participants took part in a familiarisation and two psychophysiological testing sessions, separated by a minimum of 24 hours, performed in a thermoneutral environment (ambient temperature: 25 °C; relative humidity: 45 %). To alleviate expectation bias, participants were blinded to the characteristics of each stimulus application. They were provided with information solely regarding the location of the stimulation and the characteristics of the c-WPT (i.e., the requirement to continuously rate their local wetness perception as it differed from and returned

to baseline), using an off-the-shelf data acquisition software (Daisylab, MCCDAQ, Massachusetts, USA).

During the sessions, participants took part in the c-WPT (Chapter 6), requiring them to continuously report their ongoing wetness perceptions on a VAS arising from the local application of cold-wet (23 °C) 60-second static stimuli to the underarm skin via a handheld temperature-controllable probe (surface area: 25 cm^2, Figure 34D, see Gordon et al. (2024)), with an integrated load cell to measure application force (i.e. < 1 N).

A 100% cotton patch saturated with 1 mL of either water, PG, MO, or PMX was secured on top of the probe (Figure 34B). In a randomised sequence, each stimulus application was applied to the underarm five times per fluid and visit (total of 40 repeated measures). Participants continuously reported the magnitude of their wetness perception on a digital 100 mm VAS (i.e. 0 mm; dry to 100 mm; extremely wet), sampling at 10 Hz (Figure 34C) during both the probe application phase (0 - 60 seconds) and the subsequent post-probe contact phase (> 60 seconds). The end of test time varied based on participants' subjective experiences of their underarm wetness and was determined when the sliding scale was moved back to 0 mm, which indicated dryness (average response; 47 ± 6 s).

In combination with perceptual assessments, biophysical changes in local skin temperature were continuously measured using a thermocouple board with T-type thermocouple (RS Components Ltd, Coby, UK), secured with adhesive tape in the centre of the underarm (over the midaxillary line, 10 cm above the nipple line, Figure 34A). For further setup details, refer to our methods paper (Chapter 6).

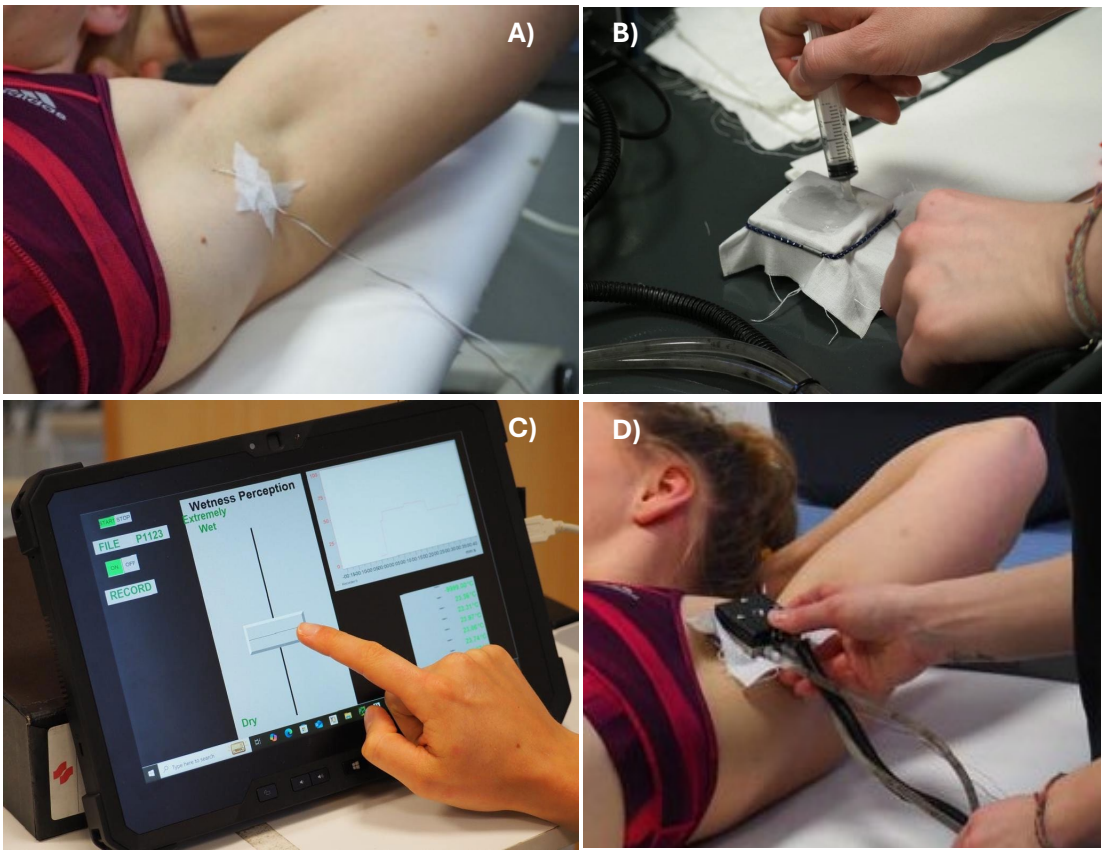

Figure 34. A) Integrated skin temperature measurements recorded over time with T-type thermocouples were applied to the underarm, B) Temperature-controlled probe with 1 ml of fluid applied to a 100 % cotton patch, C) Graphical user interface displaying the visual analogue scale used to continuously assess wetness perception, D) Probe application to the underarm.

The four fluids were chosen as they provided a range of thermal properties, specifically thermal conductivity and heat capacity (Table 8). All fluids were non-toxic, colourless, and odourless, and they were all applied at the same temperature (i.e., 23 °C) and in the same volume (1 mL). To deliver a controlled application of those fluids onto the skin, 100 % cotton patches were saturated with 1 mL of each fluid, secured onto the probe, and delivered at the given application pressure (i.e. < 1 N) onto the skin.

Table 8. Fluids' heat capacity and thermal conductivity properties.

Fluid	Thermal conductivity (W/m·K)	Heat capacity (J/g·C)
Water	0.598	4.18
PG	0.206	2.49
PMX	0.153	1.52
MO	0.136	1.67

By fixing application temperature, pressure, and contact time, our experimental design allowed to isolate the independent effects of fluid thermal properties on wetness perception responses and assessed for intra- and inter-subject variability.

Experimental Procedures

Upon arrival at the laboratory, participants' anthropometric measurements were collected. Height was measured on a wall stadiometer and weight on a precision scale (KERN 150K2DL, Balingen, Germany). Participants were then positioned supine on a therapy bed, and the testing sites were marked with a washable marker. Following this, participants were familiarised with the c-WPT and VAS using the forearm as a neutral test site (i.e., the midpoint between the wrist and antecubital fossa). The probe (23 °C) was applied to the forearm skin for 60 seconds in a randomised order with either a cold-dry cotton patch (without moisture) or a cold-wet cotton patch (saturated with 1 mL of water) secured on top. Whilst in contact with the skin, the participants were encouraged to freely adjust the sliding scale according to their level of perceived wetness. On the removal of the probe, participants were required to report their decay in wetness on the sliding scale, which lasted as long as required for participants to perceive the experience of dryness.

Upon completion of the familiarisation, testing began. First, biophysical skin parameters were taken at the underarm. These non-invasive methods included using an infrared thermometer (Spot IR Thermometer TG54; FLIR Systems, Wilsonville, OR, USA) to obtain a baseline and post-stimuli application local skin temperature measurements. The infrared thermometer was also used to measure probe-patch interface temperature to ensure the patch had achieved the target temperature of 23 °C once the fluid had been pipetted, before contact with the skin. Extensive piloting verified patch saturation levels via gravimetry and highlighted the time required for the equilibrium of the patch-probe temperature. Finally, assessments of local SCH values (Clarys et al., 2012), Corneometer; CM 825, CK Electronics, Germany) were measured at

baseline and after each fluid application (Figure 35). Following a verbal notice, the cold-wet stimuli were applied to the skin, during which the participant was prompted to continuously track their wetness perceptions, adjusting the sliding scale based on the evolving sensations. Upon the removal of the stimuli, participants were encouraged to record their decay in wetness perceptions until they perceived the experience of dryness.

Subsequently, the area of skin was dried, the cotton patch was changed, the skin was encouraged to return to baseline temperature, and the process was repeated five times for each fluid in the randomised sequence. To further reduce carryover effects, we also identified an ideal inter-stimulus interval of two minutes between repeats. The experimental protocol was identical for the second session, except for the different randomised order in which the fluids were placed on the skin. We identified five repeats to be an ideal number of repeats per stimulus because of the need to balance repeatability of wet stimulations with the potential impact of such repeated applications on changes in local SCH, local skin temperature, and the resulting skin wetness perception.

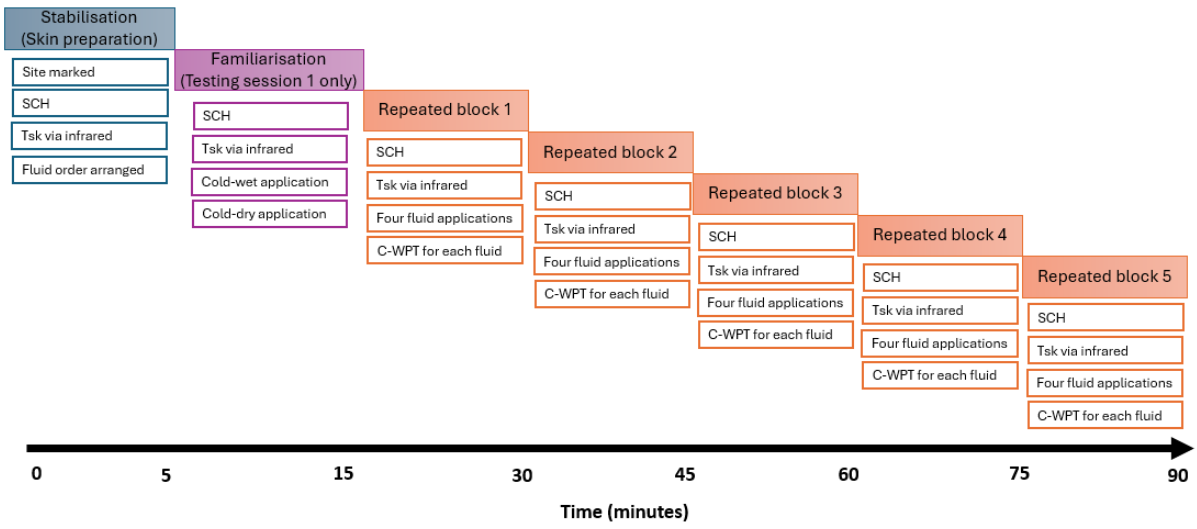

Figure 35. Schematic of experimental design in order of events. *SCH = stratum corneum hydration, Tsk = skin temperature, c-WPT = continuous wetness perception test.*

Analytical Approach to Data Analysis

Wetness Perception

The analytical approach for this study builds upon the extensive analysis conducted in the methods development paper (Chapter 6), with some variation. The PCA identified four key temporal phases of wetness perception: onset of wetness, magnitude of wetness, changes following peak wetness, and decay in wetness. Within each phase, wetness perception parameters (peak, AUC, T2R, T2Rpost, and delta) with the highest correlation coefficients were originally selected to assess test–retest reliability (ICC and MDC) and evaluate the method's sensitivity to differences in wetness perception during the application of different fluids. To extend this approach and further characterise differences in wetness perception across its full temporal profile, additional parameters were selected within the established phases where appropriate. The refined analytical approach and the reasoning for parameter selection are outlined below.

Onset of wetness: T2R will be retained, as it demonstrated the highest correlation coefficient within this phase (r = 0.707), despite no significant differences between fluids. To further explore potential fluid-related differences during wetness onset, time to peak (T2P) will also be included. T2P had the second highest correlation coefficient (r = 0.686), and quantitative observation suggests potential differences between T2R and T2P responses. Therefore, statistical analysis of T2P will provide additional insight into early-phase wetness perception.

Magnitude of wetness: Peak wetness and AUC will be retained as the primary parameters for this phase, as they were the strongest contributors and most descriptive measures of wetness magnitude.

Decay in wetness: In the methods paper, T2Rpost was selected due to its highest correlation coefficient (r = 0.871); however, no differences between fluids were observed. In the present study, time to baseline (T2B) will instead be used, as it provides a more direct and meaningful representation of wetness decay. T2B demonstrated a similarly strong correlation coefficient (r = 0.812), supporting its suitability for analysis of fluid-related differences.

Changes following peak wetness: The delta parameter will not be carried forward into this study. This component contributed only 7 % of the total variance, and the remaining three principal components still explain over 68 % of the total variance, exceeding recommended thresholds. Furthermore, no fluid-related differences were observed in delta wetness perception, indicating that further analysis of this parameter is unlikely to provide additional insight.

Overall, this refined analytical approach preserves the strongest and most meaningful parameters identified in the methods development paper, while incorporating additional measures to enhance sensitivity to temporal differences in wetness perception across fluids.

Skin Temperature

Furthermore, it was highlighted from previous research (Bergmann Tiest and Kappers, 2009, Havenith et al., 1992, Ho, 2018) that skin temperature during material contact is likely to present a Newtonian cooling pattern (Newton, 1809). The curve typically follows a similar pattern regardless of the material, or in this case, fluid, being applied to the skin. The cooling curve can be divided into different skin cooling phases, such as the rapid drop in temperature at the moment of contact (initial phase) and the slower change in skin temperature with prolonged contact (late phase) (Ho, 2018). The differences among the features during stimuli contact can be summarised as the initial rate of cooling and the total change in skin temperature (Bergmann Tiest and Kappers, 2009). Therefore, using the key components of the wetness perception trace, the relative changes in skin temperature were extracted, rather than through individual skin temperature parameters.

Therefore, the skin temperature response profile was first divided into the two main phases: initial rate of cooling (1) and total cooling (3) by fitting a linear regression to calculate the slope using distinct points in the wetness perception curve for time stamps. For example, the initial rate of cooling is linked to their T2R (≤ 6 s), and their total cooling is marked at the end of contact (= 60 s). It was then identified that the skin temperature's initial rate of cooling had two apparent elbow points before filtering into the total cooling phase. Therefore, a second rate of the cooling phase was introduced (2) in line with the T2P wetness perception data (6 s to 11s), and a linear regression was fitted to accurately represent this slope. Finally, it was of interest to investigate the rate of skin rewarming upon the removal of the stimuli (4). The T2B from the wetness perception data was used to indicate the point at which the participants felt dry, and the slope was calculated from the end of contact (60 s) and their T2B (≥ 60 s).

Statistical Analysis

Data normality and homoscedasticity were assessed using the Shapiro–Wilk and Levene tests, respectively. The wetness perception parameters, T2R, peak wetness, AUC, and T2B, and biophysical variables, rate of cooling, magnitude of cooling, rewarming rate and SCH were identified to be normally distributed; hence, parametric tests were used for the analysis.

To determine the effect of fluid on individuals' wetness perception, the selected parameters were analysed for the independent effect of fluid (four levels: water, PG, MO, PMX) and repeat (ten levels: 1 - 10) by means of two-way repeated measure ANOVA. In the event of a statistically significant main effect or interaction, a post hoc analysis was conducted using a Bonferroni correction.

To determine the effect of fluid on individuals' skin temperature, the parameters were analysed for the independent effect of fluid (four levels: Water, PG, MO, PMX) by means of one-way repeated-measure ANOVA. In the event of a statistically significant main effect or interaction, a post hoc analysis was conducted using a Bonferroni correction.

SCH data were analysed separately for the effect of time (two levels: visit 1 vs visit 2) and repeat (five levels: 1 - 5) by means of two-way repeated measure ANOVA to determine how skin hydration varied following each fluid application. In the event of a statistically significant main effect or interaction, a post hoc analysis was conducted using a Bonferroni correction.

Additionally, the T2P wetness was identified to be non-normally distributed; thus, non-parametric tests were used. These parameters were analysed for the effect of fluid and repetition by means of Friedman tests to determine how wetness perception or skin temperature (respectively) varied following the different fluid applications. In the event of a statistically significant main effect, a post-hoc analysis was conducted using Wilcoxon signed-rank tests with a Bonferroni correction.

7.4 Results

Wetness Perception and Skin Temperature Trace: Group Average

Evaluation of wetness perception responses highlighted a similar characteristic response profile to the trace determined (Chapter 6) whereby, irrespective of the fluid, wetness perception, a) had an onset following contact with the wet stimulus; b) progressed to a peak magnitude, c) which was followed by a slight decline towards the end of contact; and d) decayed at a much faster rate following stimulus removal (Figure 36).

When observing the graphs below, similar response profiles were seen with skin temperature, whereby, irrespective of the fluid, A) an initial decrease in skin temperature upon contact with the wet stimulus occurred (Component 1; initial cooling rate at T2R); B) a secondary cooling phase within the initial cooling was observed, with skin temperature decreasing at different rates based on fluid application (Component 2; secondary initial cooling at T2P); C) a

continuous decrease during the contact phase occurred (Component 3; magnitude of cooling); D) upon stimulus removal, skin temperature rose at a given rate towards baseline values (Component 4; rewarming rate, Figure 36).

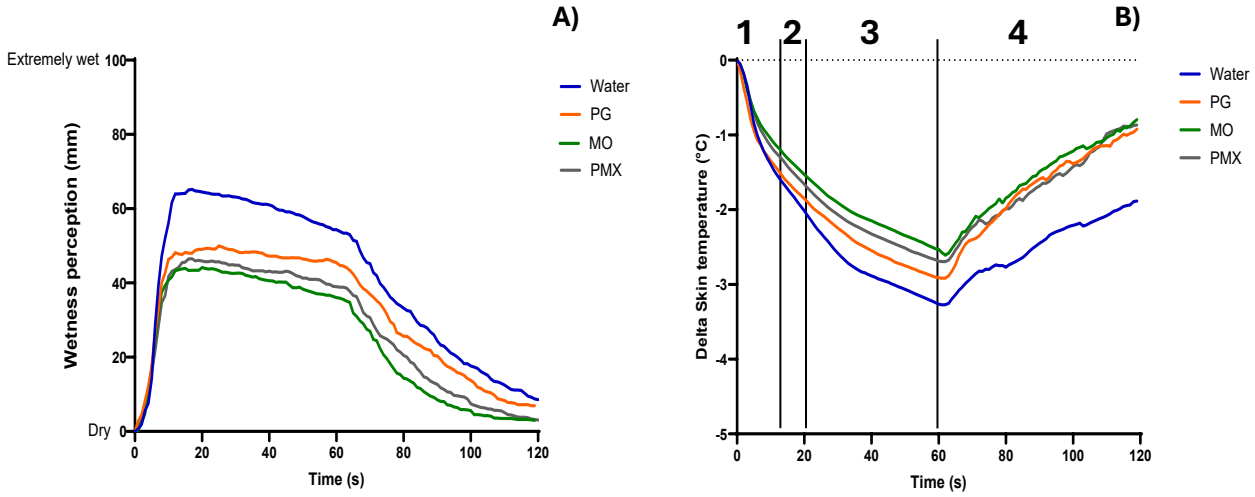

Figure 36. Presents continuous mean wetness perception (N = 15, panel A) and delta change in skin temperature (N = 15, panel B) responses during both contact and post-contact phases of our c-WPT, and in relation to each of the four fluids used. *Component 1 = initial rate of cooling; Component 2 = secondary cooling phase; Component 3 = magnitude of cooling; Component 4 = rewarming phase.*

Wetness Perception Parameters

Onset of Wetness

There was no statistically significant main effect of fluid ($F_{(3, 24)}$, = 0.265, p = 0.850), repeat ($F_{(9, 72)}$, = 1.029, p = 0.426) or interaction effect ($F_{(27, 216)}$, = 0.701, p = 0.864) in the T2R (Figure 37A) It was found that the average time it took participants to respond to the stimuli being applied to the skin of the underarm was similar across the fluids and corresponded to 6.3 (± 0.4) seconds.

Time to Peak

There was no statistically significant main effect of fluid or repeat (Chi square = 39.041, p = 0.468) on T2P (Figure 37B). It was found that the average time it took participants to reach peak wetness perception was similar across the fluids and corresponded to 10.8 (± 5.7) seconds.

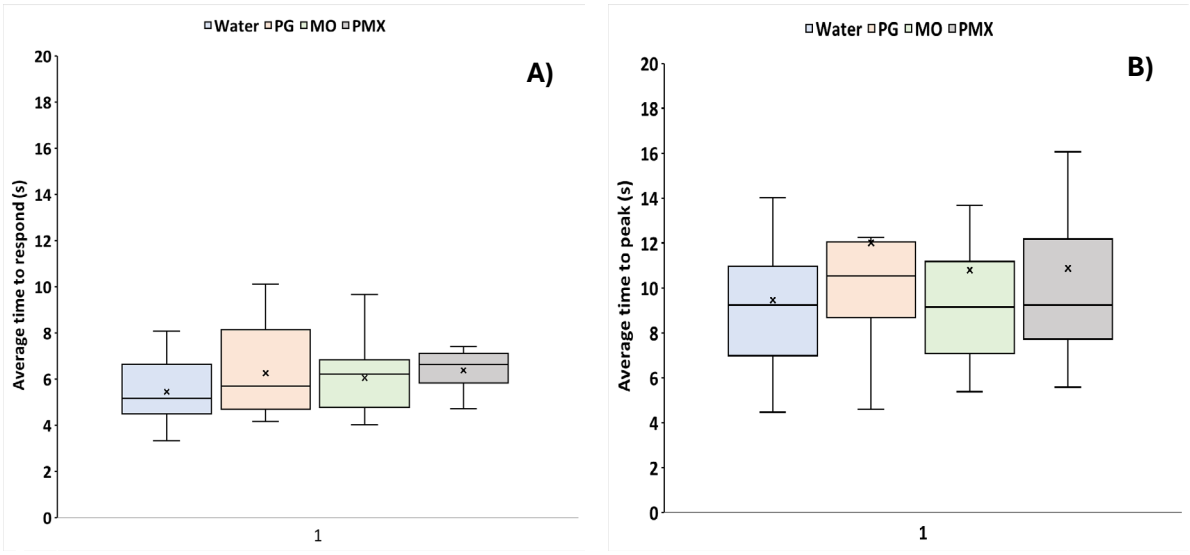

Figure 37. Representing wetness perception responses: A) time to respond, B) time to peak wetness, during 60s contact of a cold-wet stimulus separated by the four fluids (water = blue; propylene glycol [PG] = orange, mineral oil [MO] = green; dimethicone [PMX] = grey). Presented as mean, standard deviation, minimum, maximum and interquartile range.

Magnitude of Wetness

There was a statistically significant main effect of fluid ($F_{(3, 21)}$, = 13.60, $p < 0.001$) and repeat ($F_{(9, 63)}$, = 4.102, $p < 0.001$), yet no interaction effect ($F_{(27, 189)}$, = 0.643, $p = 0.913$) on peak wetness perception. Post hoc Bonferroni analysis revealed a statistically significant increase in peak wetness perception with water compared to MO (+22 mm, 95 % CI: +7.5, +36.3, $p = 0.005$) and PMX (+23 mm, 95 % CI: +4.1, +41.1, $p = 0.018$, Figure 38A). The mean difference in peak wetness for water compared to these other two fluids was 16 ± 1.7 mm, which is greater than the established MDC. Despite no statistically significant difference between water and PG (95 % CI: -1.5, +38, $p = 0.074$), there was a +18 mm increase with water compared to PG, which is outside the measurement error. Post hoc Bonferroni analysis revealed no statistically significant differences in wetness perception between the repeated applications.

Area Under the Curve

There was a statistically significant main effect of fluid ($F_{(3, 24)}$, = 14.47, $p < 0.001$) and repeat ($F_{(9, 72)}$, = 3.38, $p = 0.018$), yet no interaction effect ($F_{(27, 216)}$, = 0.767, $p = 0.601$) on the AUC for wetness perception. Post hoc Bonferroni analysis revealed a statistically significant difference in the AUC with water compared to MO (+1110 mm^2, 95 % CI: +488, +1732, $p = 0.002$) and PMX (+1134 mm^2, 95 % CI: +276, +1992, $p = 0.011$, Figure 38B). Post hoc Bonferroni analysis revealed a statistically significant difference in the AUC for repeat 1 compared to repeat 5 (+ 767mm^2, 95 % CI: +165, +1368, $p = 0.010$). The mean difference in AUC for water compared to these other two fluids was 1122 ± 17 mm^2, which is greater than the established MDC.

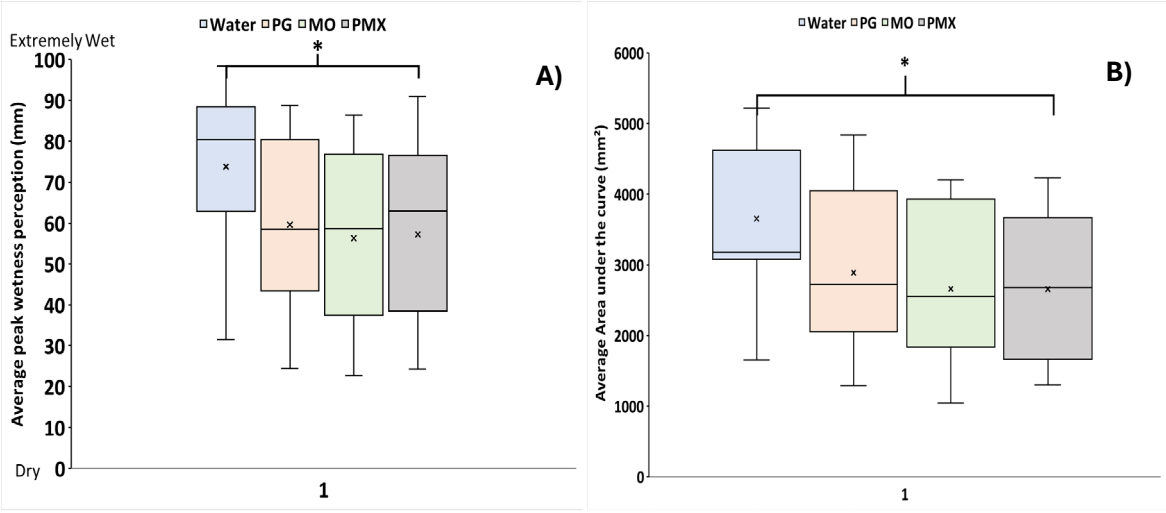

Figure 38. Representing wetness perception responses: A) peak wetness, and B) area under the curve. Data is separated by the four fluids (water = blue; propylene glycol [PG] = orange, mineral oil [MO] = green; dimethicone [PMX] = grey). Presented as mean, standard deviation, minimum, maximum and interquartile range. *Statistical significance $p < 0.05$.

Decay in Wetness

We found a statistically significant main effect of fluid ($F_{(3,18)}$ = 5.172, $p = 0.009$), however, no effect of repeat ($F_{(27,162)}$ = 0.585, $p = 0.803$) or interaction effect ($F_{(9,54)}$ = 0.880, $p = 0.639$) on T2B. Post hoc Bonferroni analysis revealed a statistically significant difference in T2B between water compared to MO (+13.8 s, 95% CI: +2.4, +25.2, $p = 0.020$, Figure 39), meaning water felt wetter for longer. Despite no statistical difference, water was 11.5 ± 3.9 s slower to reach baseline than PMX (95 % CI: -3.8, +27, $p = 0.163$), again implying this felt wetter for longer.

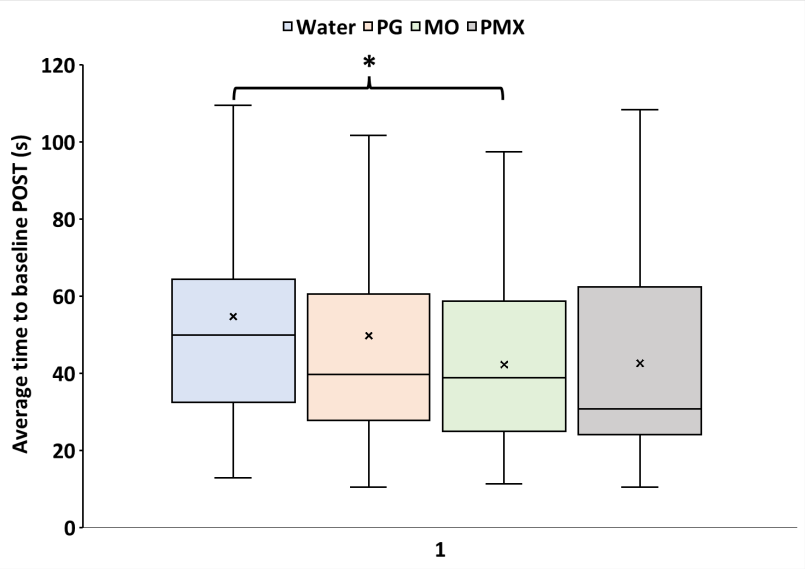

Figure 39. Representing the time to baseline wetness perception response during the removal of the probe contact. Data is separated by the four fluids (water = blue; propylene glycol [PG] = orange, mineral oil [MO] = green; dimethicone [PMX] = grey). Presented as mean, standard deviation, minimum, maximum and interquartile range. *Statistical significance $p < 0.05$.

Skin Temperature

Component 1: initial cooling rate at time to respond

The one-way repeated measures ANOVA determined that the initial rate of cooling did not differ statistically significantly between fluids ($F_{(1, 20)} = 1.20$, $p = 0.308$). The mean initial cooling rate at the T2R for wetness perception was 0.13 ± 0.013 °C/s for MO, 0.14 ± 0.015 °C/s for water, 0.19 ± 0.19 °C/s for PG, and 0.19 ± 0.052 °C/s for PMX.

Component 2: secondary cooling rate at time to peak

Secondary cooling rates were statistically significantly different amongst fluids ($F_{(2, 33)} = 3.735$, $p = 0.028$). Post hoc analysis with a Bonferroni adjustment did not reveal a statistically significant difference between secondary cooling rates. Despite no statistical differences, water (0.14 ± 0.015 °C/s) had the fastest cooling rate compared to PG (0.11 ± 0.017 °C/s), MO (0.09 ± 0.015 °C/s) and PMX (0.09 ± 0.009 °C/s).

Component 3: magnitude of cooling

There was a statistically significant main effect of fluid ($F_{(3, 27)}$, = 6.181, p = 0.002), repeats ($F_{(9, 81)}$, = 13.536, p < 0.001), and interaction effect ($F_{(27, 243)}$, = 1.581, p = 0.038) on the delta change in skin temperature during probe contact. The mean change in skin temperature during contact with water was 3.4 ± 0.4°C, followed by PG (3.0 ± 0.7 °C); PMX (2.7 ± 0.7 °C); and MO (2.6 ± 0.7 °C). Post hoc Bonferroni analysis revealed a statistically significantly greater reduction in skin temperature with water compared to MO (+0.63 °C, 95 % CI: +0.16, +1.1, p = 0.009) and PMX (+0.42 °C, 95 % CI: +0.30, +0.8, p = 0.033). Additionally, post hoc analysis revealed that the repeat also impacts skin temperature, with the reduction being greatest between repeat one compared to repeat five (+1.4 °C, 95 % CI: +0.45, +2.3, p = 0.003) and repeat six compared to repeat ten (+1.9 °C, 95 % CI: +0.85, +2.9, p < 0.001). The interaction revealed that the effect of fluid varied as a function of the repeat, as such greater differences in skin temperature for water compared to PMX (+1.1 °C, 95 % CI: +0.3, +1.9, p = 0.008), PG (+0.8 °C, 95 % CI: +0.02, +1.5, p = 0.045) and MO (+0.7 °C, 95 % CI: +0.3, +1.3, p = 0.040) during repeat four and repeat nine, respectively.

Component 4: rewarming rate

A repeated measures ANOVA with a Greenhouse-Geisser correction determined that rewarming rate did not differ statistically significantly between fluids ($F_{(2.6, 36.46)}$ = 0.675, p = 0.553). Despite no statistical significance, water had the slowest rewarming rate (0.024 ± 0.017 °C/s), followed by PMX (0.028 ± 0.013 °C/s), MO (0.029 ± 0.018 °C/s) and PG (0.031 ± 0.011 °C/s).

Stratum Corneum Hydration

Regarding SCH, a statistically significant effect of time ($F_{(8,96)}$ = 10.53, p = 0.010), yet no effect of visit ($F_{(1,12)}$ = 3.25, p = 0.074, -1.39 au mean diff) nor an interaction ($F_{(8,96)}$ = 0.92, p = 0.883) was found. Specifically, when collapsed over repeat, SCH decreased by 20.5 au, from an average baseline value of 56.3 au (95 % CI: +13.7, +21.5) to an average value of 35.8 au (95 % CI: -8.6, -32.1) after the last stimulus application.

7.5 Discussion

The study aimed to investigate how the application of fluids varying in thermal conductivity and heat capacity impacted wetness perceptions at the underarm. It was hypothesised that wetness perception at the underarm would be greater because of a higher thermal conductivity and heat capacity of the fluid being applied. Our findings support this hypothesis. First, we observed that fluid type impacted two of the wetness perception phases: the magnitude of wetness and decay in wetness. Specifically, the application of water, which had a greater thermal conductivity, triggered wetter and prolonged perceptions at the underarm compared to PMX and MO, which had the lowest thermal conductivity. In contrast, we found no impact of fluid type on wetness perception for the other phase, i.e. onset of wetness, such that the time it took the participants to respond to the stimulus was within the same time frame regardless of the fluid being applied. Second, we found that the fluid type impacted skin temperature response at the underarm; specifically, there was a greater difference in the magnitude of skin cooling between water and the other three fluids during probe contact.

These findings provide novel fundamental insights into the underarm's perceptual responses to wetness during prolonged contact with varying fluids, which could inform understanding of the determinants of wet feel and thermal comfort associated with the application of APDO products.

During Probe Contact

Onset of Wetness

Regarding our first observation, participants consistently responded to each stimulus application within ~6 s for wetness perception, regardless of the fluid applied. These findings support those in Chapter 6, whereby participants also responded within ~6 seconds during stimulus application to the forearm, demonstrating high repeatability of both skin sites. Cold-sensitive afferents carry signals via the spinal cord and thalamus to cortical regions, including the somatosensory and insular cortices, where inputs are integrated in the posterior parietal lobe and relayed to decision-making areas such as the prefrontal cortex (Kandel et al., 2000, Filingeri, 2016, McGlone and Spence, 2010, Craig et al., 2000). This processing leads to conscious wetness perceptions and subsequent feedback motor responses, to send the command via efferent neurons to the finger (Evarts, 1975), moving the sliding scale to indicate the perceived wetness level. While thermal stimuli typically elicit faster reactions (300 ms –1.99 s) (Lele and Sinclair, 1955), wetness involves more complex multimodal sensory integration and

prior experience, which may explain the longer ~6 s response time observed, independent of fluid properties. Furthermore, the absence of differences in T2R may be supported by the skin temperature data, which showed a similar average cooling rate across fluids (0.17 ± 0.003 °C/s). Filingeri et al. (2013b) reported that a cooling rate of approximately 0.14 °C/s or greater is sufficient to elicit the perception of illusory wetness. As the cooling rates observed in the present study are within this threshold and similar across fluids, this potentially limits fluid differences in T2R.

T2P wetness, irrespective of the fluid, was slower than the T2R, at around ~11 s, implying there was a ~5 s delay in their response to achieve peak wetness perception. To our knowledge, this is the first evidence of a delay in peak wetness, and therefore, to capture maximal wetness, the methodological approach needs an extended period, beyond 11 s of stimulus application on the skin and the opportunity for the participants to continuously record their wetness or move the sliding scale more than once. These results confirm the suggested observation in Chapter 6 which reported that peak wetness was likely to occur at the later contact point based on their graph, whereby the wetness perception experienced at the T2R was lower than their peak wetness. Thus, here we confirm that their T2R is their initial wetness response, not their peak wetness, and this occurred later, ~11 s. This highlights the limitations of a 10 s single time point assessment. Rather than peak wetness being observed, the single-point method is likely producing participants' initial response (Filingeri et al., 2014a, Wildgoose et al., 2021, Valenza et al., 2024). Future studies should consider which method accurately represents the data required for wetness assessment for their given research question.

Magnitude of Wetness

Our findings are consistent with previous research showing that, when moisture content is constant, cold–wet stimuli evoke stronger perceptions of wetness regardless of fluid type (Ward et al., 2025, Valenza et al., 2019, Blount et al., 2025, Christogianni et al., 2022). This reinforces the central role of thermoreceptors in mediating wetness perception through the detection of skin cooling (Filingeri and Havenith, 2015). In line with this mechanism, and an extension of this knowledge, fluids with higher thermal conductivity and heat capacity, such as water, create a greater avenue for heat exchange, likely attributable to their greater capacity to induce physical cooling of the skin, resulting in a stronger thermosensory signal and consequently enhanced wetness perception. This was experienced in this study, when observing the skin temperature cooling data, specifically the secondary phase of initial cooling at the point peak wetness is achieved, the rate of skin cooling differs, with water having the fastest rate at 0.14 ± 0.015 °C/s and producing the greatest peak wetness. The cooling rates identified in the current study align

with previous research, Filingeri et al. (2013b) investigated the role of decreasing contact temperature and skin cooling on wetness perception. They found that when the skin cooled at a rate of 0.14 – 0.41 °C/s, wetness was evoked and suggested that the rate of heat transfer from the skin and stimulus played a significant role in thermal discrimination. Therefore, it is likely to suggest that the differences in peak wetness seen in our study could be due to the rate of skin cooling, and therefore the thermal properties of the fluid. Although it is of note that the measurement for skin cooling in the study previously mentioned was not continuous nor measured during contact with the stimulus, therefore, more research should investigate skin cooling rates and wetness perception with a range of fluids in varying thermal conductivity and heat capacity to support this. Yet, studies, including this one, that have continuously measured skin temperature during contact with materials, whether solid or liquid, have experienced similar Newtonian cooling profiles (Newton, 1809). Whereby, skin temperature drops rapidly upon contact with a stimulus and slows as time passes (Ho, 2018). The rate of this initial change and subsequent larger total change in skin temperature depends on the thermal properties of the stimulus (Havenith et al., 1992, Ho, 2018, Bergmann Tiest and Kappers, 2009), and these differences in these cooling curves are the physical difference in perceived coldness among material-based studies. Likewise, in this current study, the cooling curves are driving differences in wetness perception.

Area Under the Curve

As mentioned, previous research has used a single time-point measurement to assess wetness perception, yet it has now been shown that wetness perception changes temporally during prolonged contact and decays upon the removal of the stimulus at the forearm (Chapter 6). This has allowed the development of novel wetness perception parameters, such as the AUC, and the method has been sensitive enough to establish differences amongst the fluids. Hence, for this study, the c-WPT was used to measure the time-dependent changes in wetness perception, ensuring that all data were captured. Similar to Chapter 6, the study found that, under the same environmental conditions (23 °C), stimulus application time (60 s) and pressure (< 1 N), there were differences in the AUC between the fluids at the underarm. Whereby, water had the greatest magnitude of wetness (3652 ± 1038 mm^2), followed by PG (2887 ± 1132 mm^2), PMX (2658 ± 1091 mm^2) and MO (2655 ± 1039 mm^2). Remarkably, this pattern mirrors their thermal conductivity and heat capacity properties (Table 8), highlighting the potential impact the thermal properties of a fluid could have on the development and magnitude of wetness perception during probe contact. Furthermore, skin temperature changes are dependent on the thermal properties of the fluid or object (Ho, 2016) and are likely driving these differences. As

such, higher thermal conductivity and heat capacities, like water, have higher initial cooling rates and produce lower temperatures at the end of contact, compared to those with lower thermal properties (Ho, 2016), like MO. The differences between fluids for the magnitude in wetness perception development and skin temperature cooling support this argument, and these thermal cues may assist in the discrimination of the fluid being applied in the context of wetness (Ho, 2016, Bergmann Tiest, 2015). Although, unlike the current study, this evidence is based on thermal cues used to identify solids with varying thermal properties through dual skin contact and the choice of which material felt colder (Ho and Jones, 2006, Ho, 2016, Jones and Ho, 2022, Havenith et al., 1992), through the discrimination of the wetness level based on the volume of moisture applied (Merrick et al., 2021), verbal sensory description (i.e., cold, wet, and comfortable) during dynamic fluid contact (Guest et al., 2012), or varying wet fabric exploration (Bergmann Tiest, 2015, Bergmann Tiest et al., 2012). Therefore, different fluids on the same type of fabric and their impact on wetness perception have yet to be explored until now, which can support the notion that thermal properties of the fluid are driving differences in thermal cues, and thus, wetness perception.

Post Probe Contact

Decay in Wetness

To our knowledge, this is the first study to measure the decay in wetness upon stimulus removal. The results indicated that MO felt drier sooner, and water felt the wettest for the longest. There could be a few factors impacting the lingering sensation of wetness at the underarm, such as, MO had the smallest AUC during probe contact, which is likely due to the reduced magnitude of overall skin cooling through the lower thermal conductivity and heat capacity; therefore, there is less of a gradient of skin rewarming that occurs which translates to a quicker T2B or feeling of ‘dryness’. Whereas water had the slowest skin rewarming rate (0.024 ± 0.017 °C/s), which translated to the slowest T2B (55 ± 32 s), which, on average, was 10 ± 4 s slower compared to the other fluids. Yet, water has the highest thermal conductivity and heat capacity, and therefore the greatest AUC and overall magnitude of cooling.

There does seem to be a gap in the research for the observation of skin rewarming in conjunction with the decay of wetness, in this case, or other perceptual cues. One study investigated the impact of skin rewarming rate with the removal of wet clothing or with encased wet clothing (Hagen et al., 2024). They found that skin rewarming rates were higher when the items were removed than when they were maintained against the skin, and as such, they reported a drier skin immediately upon removal, whereas the wet clothing group reported no

changes in dryness. Although this was recorded at timed intervals of every 10 minutes, until the end of the assigned testing time, and until skin temperature had returned to baseline, rather than the perceptual baseline. Additionally, water may have had a slower T2B based on its evaporative cooling capabilities upon stimulus removal. Evaporative heat loss through sweating or after contact with moisture plays a crucial role in skin cooling (Arens and Zhang, 2006, Kondo et al., 1997). Therefore, activating the thermoreceptor and signalling the presence of moisture and thus wetness on the surface of the skin (Filingeri and Havenith, 2015). Water has a high heat capacity and latent heat vaporisation, and therefore, extracts large amounts of heat from the skin during evaporation and maintains a cooler sensation over time (Filingeri et al., 2017, Charkoudian, 2003, Havenith, 1999). This could also explain why water produced the sustained perception of wetness for the longest duration of time.

Limitations

Whilst these findings have relevant applied implications, it is also worth highlighting that there are some limitations to the study. For example, the fluids selected in the study have a broad range of thermal properties and therefore, subsequently have a variety of skin penetration properties. Fluid absorption through the skin is a multifaceted process influenced by both the properties of the fluid and the conditions of the skin. SCH was measured in this study; however, the impact of fluid on changes in SCH and wetness perception was not. A recent study has shown that changes in skin hydration, particularly overhydration, at the underarm will increase wetness perception during the application of a cold-wet stimulus (- 5 °C below skin temperature, 0.8 ml of water) (Ward et al., 2025). Yet, during the current study, we saw a decrease in SCH over time for the repeated stimulus application and, therefore, unlikely to have impacted our wetness perception results. Yet, SCH was not actively manipulated like the study mentioned nor were the changes controlled for. Therefore, future studies should consider how the current findings may vary when fluids with varying thermal properties are applied to an overhydrated skin of the underarm.

Practical Applications

This study could also have practical application as APDO products tend to be applied to the underarm after a shower, which would be considered as overhydrated skin. Hence, this could be a relevant topic area to investigate to inform product design. Additionally, female participants were recruited for this study despite measuring self-reported menstrual cycle; the phase of the cycle was not controlled for. However, there is limited research on the impact of

the menstrual cycle on wetness perception, specifically, yet sensitivity to thermal cold perception threshold may decrease in the late-follicular and mid-luteal phase at the mammilla, but this effect was not seen across other areas of the body (Soderberg et al., 2006).

7.6 Conclusion

In conclusion, we have demonstrated that the newly established c-WPT with integrated skin temperature can be utilised and refined for the investigation of wetness perception at the underarm, during and following contact with wet stimuli presenting a range of thermal conductivity and heat capacity properties. Given the same moisture volume and temperature, fluids with greater thermal conductivity (i.e. water) had a greater magnitude of skin cooling and wetness perceptions at the underarm during contact. This knowledge may impact future APDO fluid choice to minimise psychological- or exercise-induced wetness perceptions at the underarm

Chapter 8 Experimental Study 5: Time- and hydration-dependent changes in skin wetness perception at the underarm during contact with individual and blended fluids varying in thermal properties.

8.1 Abstract

Optimising APDO comfort requires understanding how fluid thermal properties and skin hydration influence wetness perception during application. This study examined the effects of individual and blended fluids with differing thermal conductivities on underarm wetness perception and whether shower-induced increases in SCH modify these responses.

Twenty women continuously reported wetness perception (0 – 100 mm VAS: dry to extremely wet) during 60 s contact with cotton patches (25 cm^2) applied via a temperature-controlled probe (23 °C) with integrated skin temperature measurement. Patches were saturated with 1 mL of water, PEG, or blend. Testing was conducted before and after stratum corneum overhydration (~50 % increase) induced by a 5-min warm (34 ± 1 °C) 'shower' protocol.

The blended fluid elicited greater peak wetness perception than PEG (+21 mm) and water (+12 mm). AUC was also highest for the blend compared to PEG (+1049 mm^2) and water (+618 mm^2). SCH increased significantly over time ($p < 0.05$), although the shower protocol had limited overall effects on skin temperature and wetness responses.

Overall, the blended fluid produced greater skin temperature changes and wetness perception than individual fluids, whereas acute increases in SCH had minimal influence on perceptual outcomes.

8.2 Introduction

Experiencing wetness on the skin, whether from sweating or contact with fluids, is a well-established source of thermal discomfort and a key driver of behavioural responses in humans (Gagge, 1937, Filingeri and Havenith, 2018). This is commonly experienced at the underarm, when thermal or psychogenic sweating leads to perceived wetness, encouraging the widespread daily use of APDO to reduce sweat, odour and associated negative impacts on quality of life (Swaile et al., 2012, Watkinson et al., 2007, Teerasumran et al., 2023). Although APDO are largely effective in limiting sweat-induced wetness, their application can itself evoke an acute wetness sensation, such as when a room-temperature, wet APDO product comes into contact with the warm underarm skin, potentially reducing product comfort and acceptability (Benohanian, 2001, Teerasumran et al., 2023).

Psychophysiological research identifies that wetness perception is a learnt experience that arises from the integration of the somatosensory system, using thermo-sensory cues driven by heat exchange through skin cooling (Filingeri et al., 2014a, Filingeri et al., 2014b) and mechano-sensory cues from moisture moving across the skin (Filingeri et al., 2015c, Filingeri et al., 2015a), due to the lack of hygroreceptors (Clark and Edholm, 1985). Evidence has shown that during acute, short-duration (~10 s) application, cold-wet stimuli are consistently perceived as wetter than warm-wet stimuli at equivalent moisture contents across multiple body sites (Valenza et al., 2019, Wildgoose et al., 2021, Ackerley et al., 2012). The applicability of these wetness mechanisms to the underarm has recently received attention (Ward et al., 2025), as this region exhibits altered skin properties due to personal care routines such as repeated shaving and APDO use, which reduce skin barrier function, SCH fluctuations, and increase epidermal thickness, which may modify thermal and tactile sensitivity, thereby influencing wetness perception (Turner et al., 2007, Chaturvedi et al., 2024, Tagami, 2008, Verrillo et al., 1998). Ward et al. (2025), indicated that the mechanisms for wetness perception at the underarm do follow the same observed pattern as other regions of the body, in that the cold-wet stimuli were perceived as wetter.

Evidence has highlighted the importance of skin cooling as the main driver for wetness perception, specifically during static cold-wet application, due to the heat transfer through evaporation from the skin or conductive heat loss when in contact with a wet material (Filingeri and Havenith, 2018, Raccuglia et al., 2016). Participants use the level of skin cooling and cold sensation experienced during external stimulus contact as an indicator of the skin wetness level (Ackerley et al., 2012, Raccuglia et al., 2016, Filingeri et al., 2013b). This has been further supported by Ward et al. (2025) [Chapter 6 and Chapter 7], who observed differences in wetness perception experienced during the application of different single-component fluids on the skin

of the forearm and underarm via a temperature-controlled probe (23 °C). Wetness was assessed temporally using a continuous VAS for time-dependent changes in perception. They demonstrated that the greater the magnitude of skin cooling during stimulus contact, resulted in a greater perception of wetness. Adding to this, the differences in magnitude in skin cooling between fluids were being driven by their thermal properties, specifically thermal conductivity and heat capacity. The fluids' thermal conductivities ranged from 0.598 W/m·K to 0.136 W/m·K, with water having the highest thermal properties and greater wetness perception compared to MO, which had the lowest thermal properties and wetness perception experienced. Therefore, higher thermal properties led to a greater total change in skin temperature and increased wetness perception. Similar findings have been observed in material discrimination studies, whereby participants accurately discriminated between two solid materials (i.e. aluminium vs. wood), through static touch with their fingertip, using only thermal feedback through the total change in skin temperature (Jones and Berris, 2003, Ho, 2018). Although in many material discrimination studies, wetness perception is not measured, Tiest et al. (2012) observed that subjects found it difficult to discriminate the wetness level between fabrics (i.e. cotton vs viscose) based on thermal cues alone, likely due to the thermal conductance of the material.

As thermal cues are a key driver in wetness perception, it would be of interest to understand the effect fluid combinations might have on skin temperature cooling rates and thus, wetness perception. As such, when two single fluids are blended (i.e. water and silicone), their thermal conductivity and heat capacity changes based on the specific properties of the individual components (Kazemi et al., 2025), like those found in the chemical formulation of APDO. There is limited evidence on the effect of fluid combinations on the drive in skin temperature change and its impact on wetness perception, despite the daily use of APDO products. These findings could inform product formulation for improved thermal comfort during application.

Previous research on SCH has shown that elevated skin hydration levels modify the biophysical properties of the skin (Infante et al., 2025, Samadi et al., 2022, Gerhardt et al., 2008) and subsequently may influence sensory processing, such as wetness perception, thermal and tactile sensitivity (Bergmann Tiest and Kappers, 2009, Filingeri et al., 2014b, Verrillo et al., 1998, Ward et al., 2025). Ward et al. (2025) demonstrated that both stimulus temperature and baseline skin hydration at the underarm significantly influenced perceived wetness, with overhydrated skin increasing wetness with cold-wet stimuli only, despite identical external moisture content during warm-wet and neutral-wet application. These findings could indicate that SCH modulated their perception of wetness. Therefore, it is of interest to investigate the wetness perception response of further single-component and blended fluids with varying thermal conductivity and heat capacity properties on overhydrated skin, and whether skin hydration plays a role in how the fluids feel. This would replicate a real-world situation of

applying an APDO on overhydrated skin, like after a shower, and thus whether the product might feel wetter upon application on a hydrated biophysical state of the skin. Yet, this is unknown and would be of benefit to understand for the innovation of APDO application.

Altogether, the evidence above highlights our limited understanding of the mechanisms driving wetness perception for blended fluids at the underarm and their variation with changes in the hydration levels of the stratum corneum. Therefore, the aim of this study was to investigate the role of blended fluid thermal properties and skin hydration levels on wetness perception at the underarm in healthy female participants. It is hypothesised that wetness perceptions would be greater because of higher thermal conductivity and heat capacity properties, which would be enhanced after an increase in shower-induced SCH.

8.3 Materials and Methods

This study was approved by the University of Southampton Ethics Committee (approval no.81776). All participants provided written informed consent prior to testing. The study conformed to the ethical standards set by the Declaration of Helsinki.

Participants

Twenty non-smoking, physically active females (25 ± 5 y; 1.7 ± 0.1 cm; 66.5 ± 7.9 kg) who regularly remove their underarm hair were recruited for a randomised single-blind crossover study. Priori sample size calculation was performed using an effect size corresponding to f = 0.23 (Ward et al., 2025) combined with an $\alpha = 0.05$ and a β (power) = 0.95, which determined a minimum sample of nineteen participants. Twenty participants were recruited in case of loss to follow-up.

The volunteers had no history of sensory-related disorders or cardiovascular, neurological, or skin-related conditions (e.g., eczema). In preparation, participants refrained from applying APDO and were required to shave their underarm hair 24 hours before testing. Additionally, the participants were required to arrive at the laboratory in the least physically exerting way possible to ensure that SCH was not influenced by the mode of transport.

While empirical evidence on this topic remains limited, we acknowledged that hormonal fluctuations associated with the menstrual cycle could have impacted local sensory responses. As such, we gathered participants' self-reports of the specific day of their most recent

menstrual cycle and contraceptive use (n = 1 injection; n = 2 implant; n = 3 coil; n = 4 combined pill). Female participants were recruited for the standardisation of their hair removal process, which required them to remove their underarm hair via shaving ≥ 1 x per week. Frequent hair removal, specifically shaving, can impact SCH and epidermal thickness, which could lead to changes in sensitivity (Turner et al., 2007, Verrillo et al., 1998, Chaturvedi et al., 2024).

Experimental Design

All participants took part in a familiarisation session on a separate day, and after a minimum of 24 hours, they took part in two identical psychophysiological tests, separated by a skin overhydration 'shower' protocol, performed at 8 am in a thermoneutral environment (ambient temperature: 25 °C; relative humidity: 45 %). To alleviate expectation bias, participants were blinded to the characteristics of each stimulus application. They were provided with information solely regarding the location of the stimulation and the characteristics of the c-WPT (i.e., the requirement to continuously rate their local wetness perception as it differed from and returned to baseline), using an off-the-shelf data acquisition software (Daisylab, MCCDAQ, Massachusetts, USA).

During the sessions, participants took part in our established c-WPT (Chapter 6), requiring them to continuously report their ongoing wetness perceptions on a digital VAS (Figure 40A), arising from the local application of cold-wet (23 °C) 60-second static stimuli to the underarm skin via a handheld temperature-controllable probe (surface area: 25 cm^2, see Gordon et al. (2024)), with an integrated load cell to measure application force (i.e. < 1 N).

A 100 % cotton patch saturated with 1 mL of either water, PEG, or blend, was secured on top of the probe (Figure 40B). The three fluids applied to the skin were chosen for their diverse thermal properties, specifically thermal conductivity and heat capacity (Table 9), as such, the blended mixture falls roughly halfway between the single fluid of water and PEG, indicating how the combined effect of fluids influences wetness perception. Additionally, these fluids are regularly used in APDO formulations, so they are blended during product application. Therefore, it is important to understand how this blended fluid mixture can influence wetness perception for product application. All fluids were non-toxic, colourless, and odourless, and they were all applied at the same temperature (i.e., 23 °C) and in the same volume (1 mL).

In a randomised sequence, each stimulus application was applied to the underarm three times per fluid and c-WPT (total of 18 repeated measures). Participants continuously reported the magnitude of their wetness perception on a digital 100 mm VAS (i.e. 0 mm; dry to 100 mm;

extremely wet), sampling at 10 Hz, during both the probe application phase (0 - 60 seconds) and the subsequent post-probe contact phase (60 - 120 seconds).

In combination with perceptual assessments, biophysical changes in local skin temperature were continuously measured using a thermocouple board with T-type thermocouple (RS Components Ltd, Coby, UK), secured with adhesive tape in the centre of the underarm (over the midaxillary line, 10 cm above the nipple line, Figure 40C). For further setup details and development of the c-WPT, refer to our methods paper (Chapter 6).

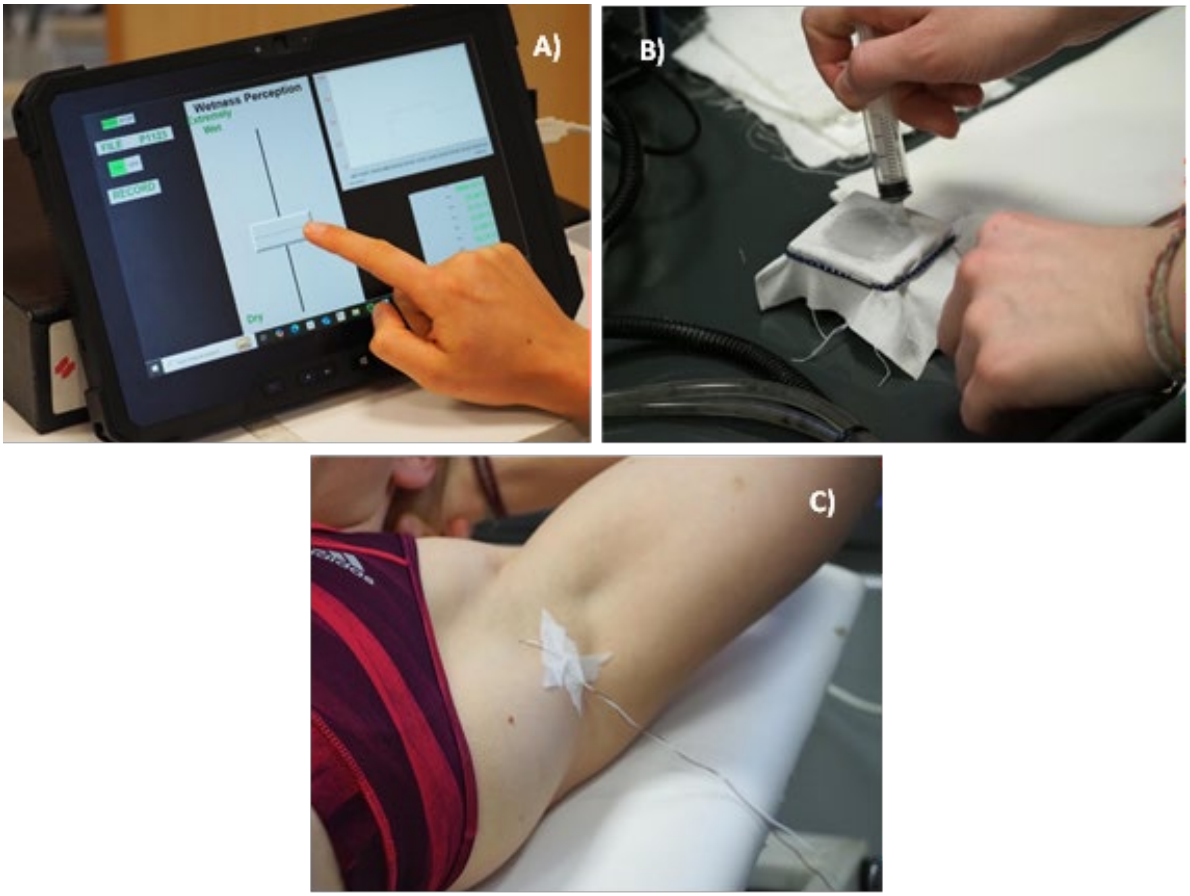

Figure 40. A) Graphical user interface displaying the visual analogue scale used to continuously assess wetness perception, during the application of the cold-wet stimulator (B), with integrated skin temperature measurements recorded over time. T-type thermocouples were applied to the skin (C).

Table 9. Fluids' heat capacity and thermal conductivity properties.

Fluid	Thermal conductivity (W/m·K)	Heat capacity (J/g·C)
Water	0.598	4.18
PEG	0.194	2.24
Blend	0.337	3.42

By fixing application temperature, pressure, and contact time, our experimental design allowed for the isolation of the independent effects of fluid thermal properties on wetness perception responses and assessed for intra- and inter-subject variability.

The overhydration 'shower protocol' consisted of running warm water (34 ± 1 °C, Figure 41) to the underarm for five minutes to mimic shower-induced changes in SCH (~50 % increase). Ward et al. (2025) (Chapter 4) found an increase in wetness perception during cold-wet application of a stimulus onto overhydrated skin, a ~20 % increase in SCH was achieved by applying a 100 % saturated cotton patch to the underarm for 30 minutes, which became the basis of the study development. As it was established that underarm skin hydration could be manipulated, extensive piloting took place to establish a protocol that replicated the real-world scenario where skin would be overhydrated, such as during a shower. Additionally, research has indicated that SCH has shown a temperature-dependent increase above 42 °C (Morin et al., 2020) therefore, the water temperature was kept below this level. Furthermore, the temperature of the water, time of day (to control for natural fluctuations in SCH) and duration of water application were explored to ensure adequate skin overhydration (≥ 20 % increase). SCH measurements were taken every hour across multiple days, which indicated that SCH was lowest in the morning before 9 am as daily activities and, thus, sweat gland activation were reduced (Yosipovitch et al., 1998). Therefore, participants arrived at the laboratory at 8 am for both sessions. Moreover, the water temperature was set to an equivalent baseline skin temperature to ensure this did not interfere with perceptual outcomes after the 'shower protocol' due to the difference in skin temperature and probe temperature gradient. Finally, the duration of water application was established via mock-up shower trials to determine the minimum amount of time required to increase SCH above 20 %.

Figure 41. Presents the overhydration 'shower protocol' at the underarm.

Experimental Procedures

Participants' anthropometric measurements were collected upon their first arrival to the laboratory, which consisted of height measured on a wall stadiometer and weight on a precision scale (KERN 150K2DL, Balingen, Germany). Participants were encouraged to find a comfortable position supine on a therapy bed with their left arm above their head, so their underarm was exposed to the ceiling, where the testing site was marked with a washable marker. Following this, participants were familiarised with the c-WPT. The probe (23 °C) was applied to the skin of the underarm for 60 seconds in a randomised order with either a cold-dry cotton patch (without moisture) or a cold-wet cotton patch (saturated with 1 mL of either water or PEG) secured on top. Whilst in contact with the skin, the participants were encouraged to freely adjust the sliding scale according to their level of perceived wetness. On the removal of the probe, participants were required to report their decay in wetness on the sliding scale, which lasted as long as participants perceived the experience of dryness. This was repeated five times per condition (cold-dry, cold-water, cold-PEG), therefore 15 stimulus applications.

Upon completion of the familiarisation session, participants returned to the laboratory at least 24 hours later for their testing session. First, a series of non-invasive biophysical skin measurements was set up and collected. In addition to the continuous measurement of local skin temperature using a thermocouple during stimulus application and removal, an infrared thermometer (Spot IR Thermometer TG54; FLIR Systems, Wilsonville, OR, USA) was used to obtain baseline and post-stimulus application local underarm skin temperature measurements. Furthermore, the infrared thermometer was used to measure probe-patch interface

temperature to ensure the patch had reached the target temperature of 23 °C once the fluid had been pipetted on top, which was repeated before each stimulus application. Local SCH using a Corneometer (CM 825, CK Electronics, Germany) for capacitance of the skin surface, was measured at the start of testing for baseline measurement and following each stimulus application for the first repeated application and then after each subsequent round of fluid repeats (Figure 42).

At this point, the QST of wetness perception was performed on a continuously recording VAS [c-WPT, i.e. 100-mm wetness scale with anchor points: dry (0) to extremely wet (100)]. Participants were given a verbal notice, and the cold-wet stimuli were applied to the skin of the underarm for 60 seconds, during which participants were encouraged to continuously track their wetness perceptions, altering the sliding scale in accordance with the development and decay of their perceptions during the probe contact phase. Additionally, upon removal of the stimuli (post-probe contact phase), participants were prompted to adjust the sliding scale until they experienced dryness (0 = c-WPT). The area of skin was dried and rewarmed to baseline skin temperature. At this time, the cotton patch was changed, and the next fluid was applied to the skin. This was repeated three times per fluid, therefore a total of nine repeats (repeat stimuli block 1 - 3, Figure 42).

Once the first QST had been completed, the thermocouple was removed from the underarm in preparation for the overhydration 'shower protocol'. The participants continued to lie supine, with their underarm exposed to the ceiling, with their body shifted slightly off the top end of the bed to allow the water to run into the water collection point. The water was run freely for five minutes to ensure it had reached the application temperature (34 ± 1 °C), then the hose was moved above the underarm and the water ran across the skin for five minutes (Figure 41), ensuring full coverage across the testing area. Before the shower protocol and immediately after, SCH and skin temperature (using an infrared camera) were recorded. Lastly, the thermocouple was reapplied to the skin site, using the same marker point.

Finally, the QST for wetness perception was repeated identically for the post-shower phase. The same three fluids were further repeated on the skin three times (repeated stimuli blocks 4 - 9, Figure 42), exactly as described before the shower protocol; therefore, the total number of repeated stimulus applications for the testing session was 18 per fluid.

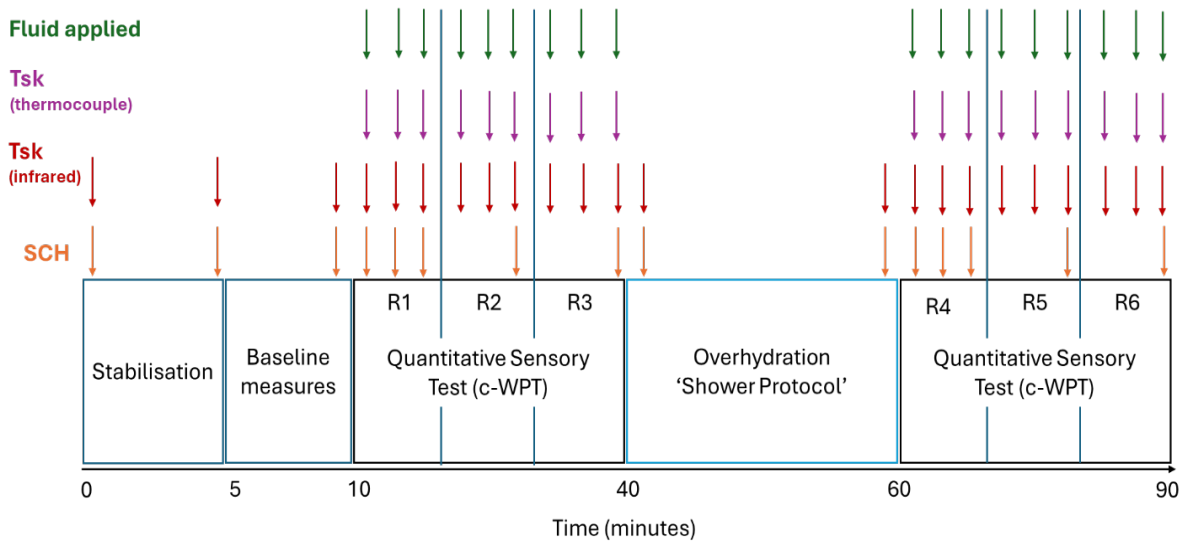

Figure 42. Schematic to describe the experimental procedure. *SCH = stratum corneum hydration, Tsk = skin temperature, c-WPT = continuous wetness perception test, R1 - R6 = repeated stimuli blocks.*

Analytical Approach

The analytical approach used in the present study was directly informed and built upon the statistical analysis from the methods development work and Study 4 (described in Chapter 6 and Chapter 7) ensuring methodological consistency and comparability across studies. Specifically, the selection of wetness perception parameters was guided by the PCA-derived temporal phases and the strength of their correlation coefficients, with key parameters such as T2R, T2P, peak, AUC, and T2B. Furthermore, an analytical approach for the skin temperature response profile, such as Component 1: initial cooling rate at T2R, Component 2: secondary initial cooling at T2P, Component 3: total magnitude of cooling, Component 4: rewarming phase, was also guided by work presented in Study 4 (Chapter 4). These wetness perception and skin temperature parameters were retained to maintain alignment with the previously established analytical framework (see 7.3). This consistency also ensures that any observed differences in wetness perception can be attributed to experimental manipulations, thereby strengthening the overall robustness of the findings.

Statistical Analysis

Data normality and homoscedasticity were assessed using the Shapiro–Wilk and Levene tests, respectively. The wetness perception and integrated skin temperature data were separated into during-probe contact parameters (T2R, peak wetness, AUC, initial rate of cooling and total magnitude of cooling) and post-probe contact phase (T2B and rewarming rate). Wetness perception, skin temperature parameters and SCH were identified to be normally distributed; therefore, a parametric test was used for the analysis. To determine the effect of fluid on an individual's wetness perception and skin temperature, the parameters were analysed for the independent effect of fluid (three levels: water, PEG, blend) and shower (two levels: pre-shower and post-shower) by the means of a two-way repeated measures ANOVA. In the event of a statistically significant main effect or interaction, a post hoc analysis was conducted using a Bonferroni correction.

SCH data were analysed separately for the effect of time (two levels: pre-shower and post-shower) and repeat (five levels: baseline, average pre, pre-shower, post-shower and average post) by means of one-way repeated measure ANOVA to determine how skin hydration changed over time. In the event of a statistically significant main effect or interaction, a post hoc analysis was conducted using a Bonferroni correction.

Additionally, the T2R to wetness perception and skin temperature Components 2 and 4 were identified to be non-normally distributed; thus, non-parametric tests were used. These parameters were analysed for the effect of fluid and shower by means of the Friedman test to determine how wetness perception varied following the different fluid applications. In the event of a statistically significant main effect, a post-hoc analysis was conducted using Wilcoxon signed-rank tests with a Bonferroni correction.

All data were analysed using SPSS Statistics 19 (version 28.1, Chicago, USA). Statistical significance was set at $p < 0.05$, and data were reported as means, SD and 95 % CI.

8.4 Results

Stratum Corneum Hydration

There was a statistically significant main effect of time ($F_{(1, 19),}$ = 58.954, p < 0.001). Post hoc Bonferroni analysis revealed that SCH significantly increased over time from the arrival phase to post-shower repeats (Figure 43A). The pre-shower phase had an average SCH of 57 ± 2 au (95 % CI: +52, +62), compared to SCH taken post shower 84 ± 2 au (95 % CI: +80, +87) with inter-individual variability (Figure 43B).

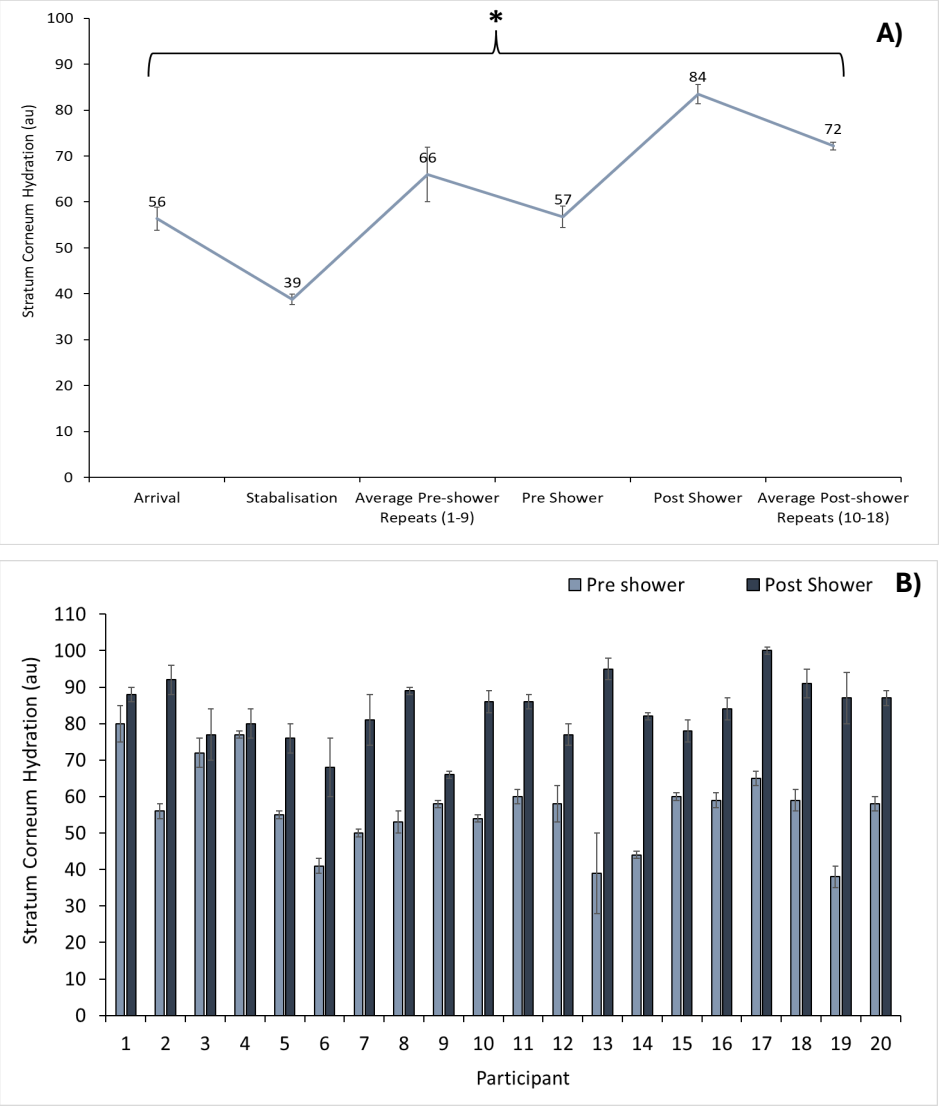

Figure 43. A) Representing the average SCH across the 6 phases of the protocol for all the participants (N = 20) and fluids (n = 3). B) Represents individual pre-shower and post- shower stratum corneum hydration values. Presented as mean (n = 3) and standard deviation. *Statistical significance p < 0.05.

Wetness Perception and Skin Temperature Overview: Group Average

Evaluation of these responses highlighted a similar characteristic response profile to the trace determined by Chapter 6 and Chapter 7. Regardless of fluid type and hydration status, wetness perceptions were characterised by: (a) an onset following contact with the wet stimulus; (b) a progression to a peak in wetness magnitude; (c) a slight decline towards the end of the contact period; and (d) a rapid decay following stimulus removal.

Comparable response profiles were seen with skin temperature, irrespective of the fluid and hydration status of the skin. This comprised of: A) an initial decrease in skin temperature upon contact with the wet stimulus (Component 1; initial cooling rate at T2R); B) a secondary cooling phase within the initial cooling period, during which the rate of temperature decrease varied according to the applied fluid (Component 2; secondary initial cooling at T2P); C) a continued decrease in skin temperature throughout the contact phase (Component 3; magnitude of cooling); D) a progressive increase in skin temperature toward baseline values following stimulus removal (Component 4; rewarming rate, Figure 44).

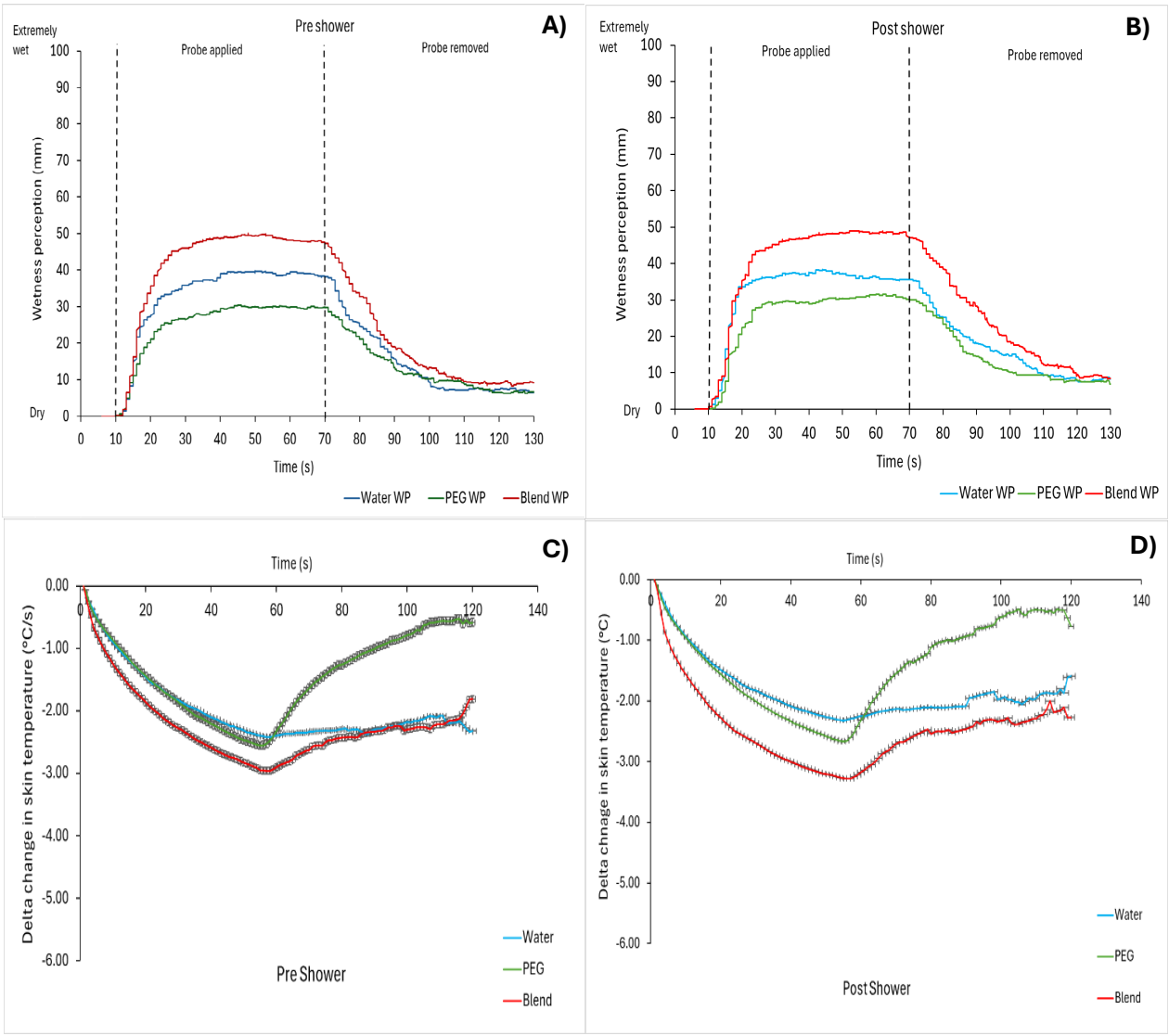

Figure 44. Presents continuous mean wetness perception (N = 20) pre-shower (A) and post-shower (B). The delta changes in skin temperature (N = 20), pre-shower (C) and post-shower (D) responses during both contact and post-contact phases of our c-WPT, and in relation to each of the 3 fluids used.

Wetness Perception

Onset of Wetness

There was no statistically significant difference in T2R between fluids whilst the stimulus was being applied to the skin, $\chi^2(5) = 8.526$, $p = 0.130$, Figure 45A. Nor were there any differences between fluids from pre to post shower (8.0 ± 0.1s).

Time to Peak

There was no statistically significant main effect of fluid ($F_{(2, 32)}$, = 2.029, p = 0.148), shower ($F_{(1, 16)}$, = 1.58, p = 0.226), or interaction effect ($F_{(2, 32)}$, = 0.296, p = 0.745, Figure 45B) on the T2P wetness perception. There was little difference in the average T2P for pre-shower (23.5 ± 3.5 s) compared to post-shower (21.8 ± 3.3 s).

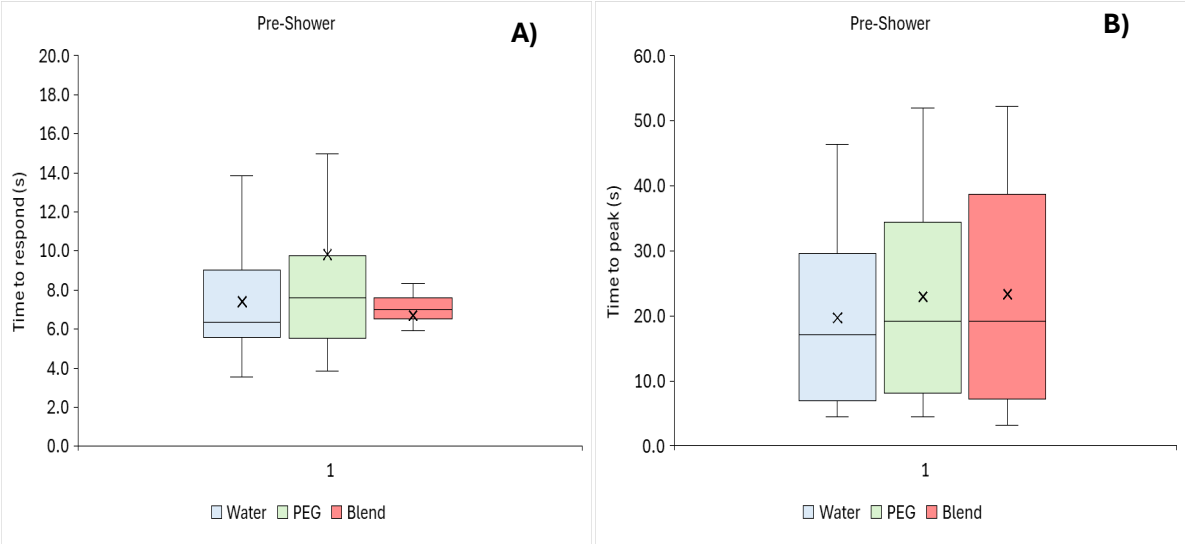

Figure 45. Representing wetness perception responses: A) time to respond, B) time to peak wetness, during 60 s contact of a cold-wet stimulus separated by the three fluids (water = blue; polyethene glycol [PEG] = green, 50/50 water/PEG [Blend] = red. Presented as mean, standard deviation, minimum, maximum and interquartile range.

Magnitude of Wetness

There was a statistically significant main effect of fluid ($F_{(2, 32)}$, = 23.0, p < 0.001), yet no effect of shower ($F_{(1, 16)}$, = 0.068, p = 0.798), or interaction effect ($F_{(2, 32)}$, = 0.169, p = 0.845) on peak wetness perception. Post hoc Bonferroni analysis revealed a statistically significant increase in peak wetness perception with blend compared to PEG (+21 mm, 95 % CI: +12, +29, p < 0.001) and water (+12 mm, 95 % CI: +3, +21, p = 0.007), and water compared to PEG (+8 mm, 95 % CI: +2, +15, p = 0.01, Figure 46A). The mean difference in peak wetness for the blend compared to these other two fluids was 10 ± 3 mm, which is greater than the established MDC.

Area Under the Curve

There was a statistically significant main effect of fluid ($F_{(2, 32)}$, = 29.56, $p < 0.001$), yet no effect of shower ($F_{(1, 16)}$, = 0.029, $p = 0.867$), or interaction effect ($F_{(2, 32)}$, = 0.005, $p = 0.995$) on the AUC. Post hoc Bonferroni analysis revealed a statistically significant increase in the AUC with blend compared to PEG (+1049 mm^2, 95 % CI: +654, +1446, $p < 0.001$) and water (+618 mm^2, 95 % CI: +232, +1005, $p = 0.002$), and water compared to PEG (+430 mm^2, 95 % CI: +119, +741, $p = 0.006$, Figure 46B). The mean difference in peak wetness for the blend compared to these other two fluids was 833 ± 304 mm^2, which is greater than the established MDC. However, the difference between water and PEG is within the error of measurement.

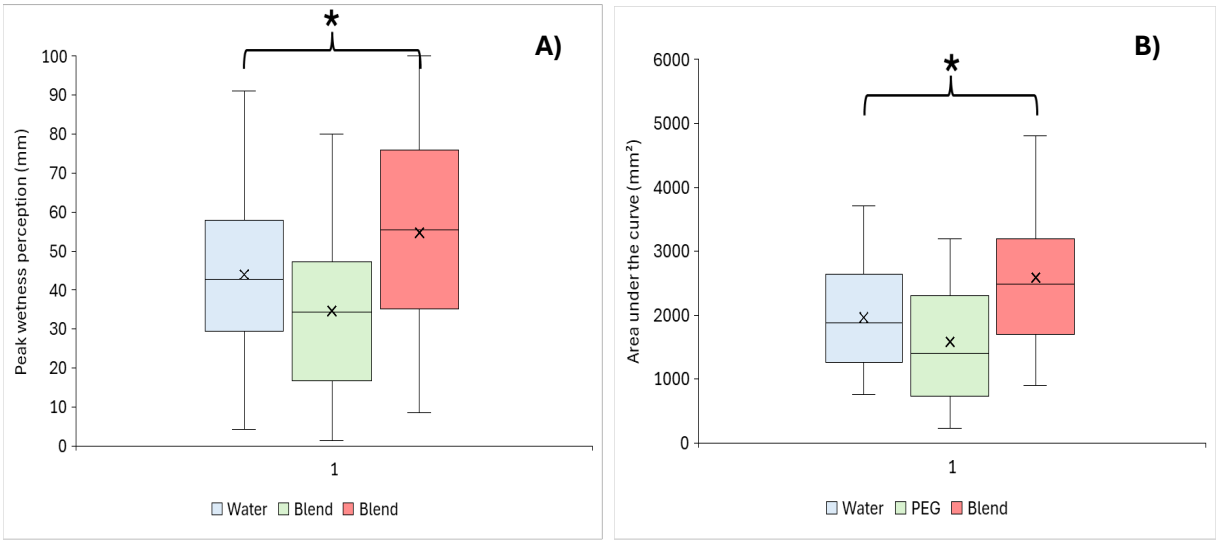

Figure 46. Representing wetness perception responses: A) peak wetness, B) area under the curve, during 60 s contact of a cold-wet stimulus separated by the three fluids (water = blue; polyethene glycol [PEG] = green, 50/50 water/PEG [Blend] = red. Presented as mean, standard deviation, minimum, maximum and interquartile range. *Statistical significance $p < 0.05$.

Decay in Wetness

A statistically significant main effect of shower ($F_{(1, 17)} = 7.397$, $p = 0.015$), however, no effect of fluid ($F_{(2, 34)} = 1.679$, $p = 0.202$) or interaction effect ($F_{(2, 34)} = 1.241$, $p = 0.302$) was found on T2B. Post hoc Bonferroni analysis revealed a statistically significant difference in T2B between pre-shower and post-shower (+5.4 s, 95 % CI: +1.2, +9.6, $p = 0.015$, Figure 47). The difference in T2B between pre- and post-shower is within the previously established range of measurement error.

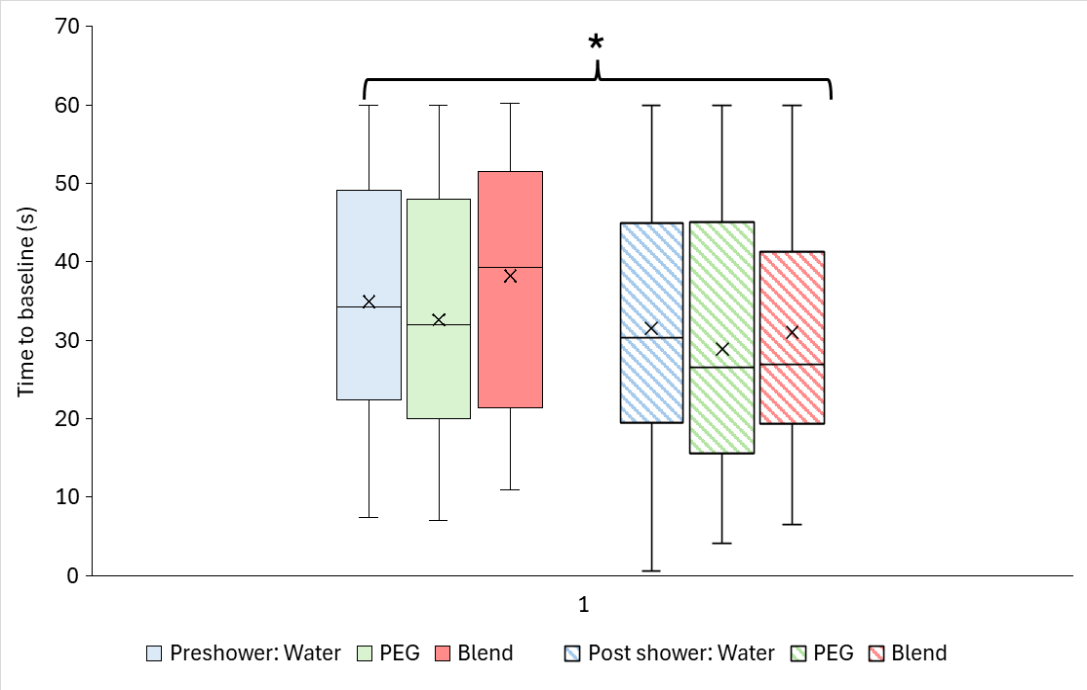

Figure 47. Representing wetness perception time to baseline responses: pre-shower and post-shower, during 60 s contact of a cold-wet stimulus. Presented as mean, standard deviation, minimum, maximum and interquartile range. *Statistical significance $p < 0.05$.

Skin Temperature

Component 1: initial cooling rate at time to respond

The two-way repeated measures ANOVA determined that the initial rate of cooling differed statistically significantly between fluids ($F_{(1, 29)} = 15.87$, $p < 0.001$), yet no effect of shower ($F_{(1, 20)} = 2.92$, $p = 0.103$) or interaction effect ($F_{(1, 30)} = 2.87$, $p = 0.068$) was found. Post hoc Bonferroni analysis revealed a statistically significantly greater rate of initial cooling with blend compared to water (+0.08, 95 % CI: +0.029, +0.135, $p = 0.002$) and PEG (+0.09, 95 % CI: +0.036, +0.137, $p < 0.001$). The mean initial cooling rate at the time for wetness perception response before the shower was slowest for PEG (0.11 ± 0.01 °C/s), followed by water (0.12 ± 0.01 °C/s), and blend (0.19 ± 0.04 °C/s).

Component 2: secondary cooling rate at time to peak

The statistical analysis determined that secondary cooling rate did differ statistically between fluids $\chi^2(5) = 11.376$, $p = 0.044$. Post hoc analysis with Wilcoxon signed-rank tests was

conducted with Bonferroni correction applied, resulting in a significance level set at $p = 0.008$. A main effect was present, but the multiple comparisons did not reach a Bonferroni-corrected threshold. The median (IQR) rate of skin cooling at peak wetness perception for the fluids was: Blend (0.07 ± 0.01 °C/s), water (0.06 ± 0.00 °C/s), and PEG (0.06 ± 0.01 °C/s).

Component 3: magnitude of cooling

There was a statistically significant main effect of fluid ($F_{(1, 31)}$, = 84.191, $p < 0.001$), yet no effect of shower ($F_{(1, 19)}$, = 1.926, $p = 0.181$), and interaction effect ($F_{(1, 35)}$, = 1.671, $p = 0.202$) on the delta change in skin temperature during probe contact. The mean change in skin temperature during contact with blend was 5.2 ± 0.2 °C, followed by PEG 3.9 ± 0.2 °C and water 3.2 ± 0.2 °C. Post hoc Bonferroni analysis revealed a statistically significantly greater reduction in skin temperature with blend compared to water (+2.0 °C, 95 % CI: +1.53, +2.4, $p < 0.001$) and PEG (+1.31 °C, 95 % CI: +1.0, +1.6, $p < 0.001$), and with PEG compared to water (+0.7 °C, 95 % CI: +0.23, +1.1, $p = 0.002$).

Component 4: rewarming rate

The statistical analysis determined that the rewarming rate did differ statistically between fluids $\chi^2(5) = 54.302$, $p < 0.001$. Post hoc analysis with Wilcoxon signed-rank tests was conducted with Bonferroni correction applied, resulting in a significance level set at $p = 0.008$. The median (IQR) rate of skin cooling and rewarming for the fluids pre-shower was: Blend (0.02 ± 0.01 °C/s), water (0.01 ± 0.00 °C/s), and PEG (0.03 ± 0.00 °C/s). There was a statistically significant difference between PEG and water ($Z = -3.92$, $p < 0.001$), and blend ($Z = -3.74$, $p < 0.001$) pre-shower, but no differences between fluids post-shower ($p = 0.008$).

8.5 Discussion

The study aimed to investigate how the application of either single or blended fluids, varying in thermal conductivity and heat capacity, impacted wetness perceptions at the underarm, and how this may change when the skin is overhydrated, such as after showering. It was first hypothesised that wetness perception at the underarm would be greater because of a higher thermal conductivity and heat capacity of the fluid being applied. Secondly, it was hypothesised that the shower protocol would overhydrate the skin and increase wetness perception during

probe contact. Our findings did not support these hypotheses, yet they offered some unexpected insights.

First, we observed that the fluids impacted the magnitude of wetness. Specifically, the application of the blend triggered wetter and prolonged perceptions at the underarm compared to the single fluids PEG and water. In contrast, we found no impact of fluid type on wetness perception for the other two phases: onset of wetness and decay in wetness. Second, we found the fluid type impacted skin temperature response at the underarm. Specifically, the magnitude of skin temperature cooling during probe contact, with the blend having the greatest reduction in skin temperature compared to the other two fluids. Finally, it was observed that the shower influenced the decay in wetness, in particular, the post-shower T2B was slower across the fluids, with the greatest effect on the blend.

These findings provide novel fundamental insights into the underarm's perceptual responses to wetness during prolonged contact with single and blended fluids. The blended fluid created a greater change in skin temperature and thus a greater perception of wetness, with no difference in response after the shower protocol. This implies that wetness perception was being driven by skin temperature change rather than the thermal properties of the fluid. These findings could inform formulation design for improved thermal comfort associated with the application of APDO products.

Impact of Fluid

Regarding our first observation, the greatest wetness perception responses were seen during the application of the blend, which is likely due to the increased magnitude of skin cooling during contact, rather than the thermal properties of the fluid, which was previously described to be driving differences in skin cooling and wetness perception response (Chapter 7). Water had the highest thermal conductivity and heat capacity, yet our findings contrast with those of Chapter 7, whereby peak wetness perception and AUC were greatest with water. They indicated that the high thermal properties influence the heat exchange gradient between the fluid and the skin, cooling the skin to a greater extent and thus perceiving a greater wetness perception. Here, we found that the blend had the largest peak wetness and AUC, followed by water and PEG, yet had lower thermal properties than water but greater than PEG. Consequently, a different fluid property might be driving the change in skin temperature and greater wetness perception responses. A proposed theory could link to the endothermic and exothermic responses that the PEG and water displayed when being mixed. When blended, the fluid's temperature rose, indicating the exothermic process of breaking and forming new bonds between atoms, which

occurs when more energy is released into the surrounding environment than is taken in (Gray, 2018). The fluid cooled to ambient temperature before being placed on the cotton patch, yet the exothermic process may have altered the physical structure and properties of the fluid. Nevertheless, the key thing to note is that skin temperature is driving wetness perception differences, which were unexpectedly experienced to a greater extent with the blend than with the other two single fluids. The exact mechanism for the greater total skin cooling for the blend is still unknown. The skin cooling rates observed in this study are similar to previous research, with an initial rate of cooling of 0.14 °C/s and 0.02 °C/s for the rewarming phase (Filingeri et al., 2013b) (Chapter 7). The exception lies with Component 3: the magnitude of skin cooling. In our study, we observed a total magnitude of skin cooling of 5.2 °C for the blend, followed by PEG (3.9 °C) and water (3.2 °C). In the previous study, the greatest magnitude was 3.4 °C for water, which is not too dissimilar from the current study. In both studies, wetness perception was highest with the greatest total change in skin temperature, again alluding to the theory that changes in skin temperature are the main driver in differences in the magnitude of wetness perception rather than the thermal properties of the fluids themselves.

When observing the 'onset of wetness phase', participants responded to stimulus application in ~8 s, with no differences between fluids or pre- and post-shower protocols, consistent with previous underarm and forearm studies reporting responses within ~6 s (Chapter 6 and Chapter 7). As wetness is a learnt multisensory experience (Filingeri et al., 2014b), the integration of thermo- and mechanoreceptive inputs likely introduces a cognitive processing delay before conscious detection (Filingeri, 2016, McGlone and Spence, 2010, Kandel et al., 2000), resulting in slower response times than for single sensory modalities such as cold detection, which can occur within ~0.5 s when cooling rates are high (Lele and Sinclair, 1955, Yarnitsky and Ochoa, 1991). Although significant differences in the initial rate of skin cooling were observed between fluids—fastest for the blend (0.16 ± 0.11 °C/s) compared with water (0.12 ± 0.07 °C/s) and PEG (0.10 ± 0.05 °C/s)—this did not lead to earlier wetness perception, supporting previous findings that T2R may not be driven by the initial phase of skin cooling or fluid type but rather by a neurological sensorimotor control loop (Chapter 6 and Chapter 7). Following initial detection, T2P wetness occurred ~14 s later, consistent with earlier work and highlighting the importance of continuous wetness perception scales during prolonged stimulation (Chapter 6 and Chapter 7). The longer T2P observed here (~11 s slower than previous underarm data and ~7 s slower than forearm estimates) likely reflects inter-individual variability and differences in cooling dynamics, as the average skin cooling rate at T2P was slower in the present study (0.05 °C/s) than previously reported for the underarm (0.10 °C/s). Although an overall effect of fluid on cooling rate at T2P was detected, pairwise differences could not be distinguished, and evidence describing the temporal development of peak wetness remains limited; however, similar pain

studies using continuous scales report site-dependent times to peak sensation (~10 – 20 s), reinforcing the need to characterise the full temporal dynamics of wetness perception rather than relying on discrete or averaged measures (Daguet et al., 2020).

Impact of the Shower Protocol

Secondly, it was observed that the shower influenced the decay in wetness, in particular, the post-shower T2B was slower across the fluids. Although greater levels of stratum corneum hydration were achieved in the present study compared to previous work, the findings contrast with earlier reports showing increased wetness or tactile sensitivity with overhydrated skin (Ward et al., 2025, Wildgoose et al., 2021, Verrillo et al., 1998). For example, Ward et al. (2025) observed enhanced wetness perception at the underarm during short-duration static cold–wet stimulation following overhydration; however, no such amplification was evident in the current study, despite higher SCH values. This discrepancy may reflect methodological differences, as prior work relied on single time-point measures within the first 10 seconds of contact, whereas the present study assessed multiple temporal parameters across the full perceptual profile. Similarly, Wildgoose et al. (2021) reported reduced wetness sensitivity in older adults with distinctly decreased skin hydration (~79 %), highlighting the complexity of hydration–perception interactions. In addition, these studies primarily examined water alone, whereas the current study compared multiple fluids and found that their relative behaviour remained consistent following overhydration. Collectively, these differences suggest that the influence of skin hydration on wetness perception may depend on stimulus duration, measurement approach, and fluid characteristics, warranting further investigation.

One parameter in the current study observed an effect of the shower protocol, T2B, which is the decay in wetness perception back to 0 mm (i.e. dry) on the VAS once the probe had been removed. There was no fluid effect, yet the average pre-shower T2B was 8 s slower than the average post-shower T2B. It has been established in previous research that skin hydration changes the mechanical properties of the skin, in tactile sensitivity, surface roughness and transepidermal water loss (Verrillo et al., 1998, Wildgoose et al., 2021, Samadi et al., 2022, Camilion et al., 2022). Despite not measuring these parameters, it could be possible that a change in skin structure and tactile cues could have altered their wetness perception, specifically less lingering sensation once the probe was removed after the shower protocol. The shower protocol provided a unique method to assess overhydration of the underarm skin in a practical setup that replicated a real-world setting. Despite aiming to alter SCH to a greater extent pre-to post-shower, the effect of the shower was limited, and there was not a dramatic difference in pre (57 ± 2 au) to post-shower (84 ± 2 au), likely due to the nature of the repeated

fluid application during the QST for the wetness perception assessment. Previous research has highlighted the need for repeated stimuli application for the reliability of the continuous quantitative sensory assessment (Burge and Bonnen, 2025, Chen et al., 2025). Therefore, as the main aim of the study was to investigate how applying combined and single fluids to the underarm skin may impact wetness perception, the method was designed in favour of a reliable methodology to assess differences in wetness perception across multiple repeats.

Limitations

The study was first designed to assess wetness perception for different fluids, such as single and blended combinations. To ensure repeatability and reliability of the study, the fluids were repeated on the skin multiple times. Therefore, this might have created a limitation of the study design for the shower protocol. As such, there was a natural positive drift in the SCH across time due to the repeated fluid applications. Hence, the pre-shower SCH was not too dissimilar to the post-shower levels, which can be reflected in the wetness perception data. A greater effect of the shower might have been seen on wetness perception if the stratum corneum was similar to their arrival/post-stabilisation value. Although even with that being said, their skin hydration was elevated before the shower protocol, we were still able to increase their skin hydration to a greater extent. Thus, to assess the impact of shower or, in this instance, overhydration of the underarm on wetness perception, the repeated stimulus applications should be removed to reduce the natural increase in SCH and thus, focus on creating a greater difference in the pre-to post-shower protocol SCH.

Future Research and Application

Future research could consider furthering this knowledge area by investigating other fluid two or three blend combinations to unpick whether the differences in wetness perception, due to the large magnitude of change in skin temperature, and whether other fluid properties such as viscosity, surface tension and contact coefficients might impact the results. This and future studies have practical applications, as APDO products tend to contain a mixture of blended fluids, therefore altering the thermal conductivity and heat capacity of the formulation, and thus, impacting skin temperature cooling and wetness perception. Therefore, understanding the mechanisms that underpin wetness perception during prolonged contact with blended fluids at the underarm could inform product design for APDO application.

8.6 Conclusion

In conclusion, we have demonstrated that blended fluids impact the magnitude of skin cooling and thus, the magnitude of wetness perception experienced. Furthermore, the thermal properties of either the single or combined fluids are less likely to drive the differences in wetness perception, and rather, it is the rate of skin cooling. Secondly, it can be concluded that the fluids behaved similarly, from pre-shower or post-shower, except for the wetness perception parameter T2B, which was quicker after the shower protocol. However, there was a limited effect of the shower-induced stratum corneum changes across the skin temperature and wetness perception results, which needs to be considered when describing the T2B data. The main findings can conclude that the blended fluid induced greater differences in the rate of skin temperature change and the magnitude of wetness during probe contact compared to the single fluids. These novel findings further expand our understanding of the relationship between skin temperature and wetness perception during prolonged fluid application, which involves a range of thermal conductivity and heat capacity properties. Informing APDO formulations for product thermal comfort and application design.

Chapter 9 Discussion, Translation, and Future Research Directions

9.1 Thesis Summary and Original Contributions to Knowledge

Thesis Summary

This PhD project aimed to evaluate wetness perception at the underarm using external stimuli contact for the role of skin biophysical and fluid thermal properties. It has enhanced our fundamental knowledge of the mechanisms that underpin wetness perception at the underarm for APDO application.

Together, these findings demonstrate that underarm wetness perception is shaped by interactions between skin biophysical properties—particularly hydration and hair coverage—and the thermal properties of applied fluids, primarily through skin cooling. Cold-wet stimuli were consistently perceived as wetter, with overhydrated skin amplifying this effect during short-duration (~10 s) contact. Whilst the development and refinement of the c-WPT provided novel findings that wetness perception changes temporally, with key perceptual phases established during the extended stimuli contact (~60 s), such as onset, magnitude and decay in wetness. In addition, the rate and magnitude of skin cooling from different fluid formulations (single and blended combinations) emerged as key drivers of enhanced wetness perception, informing the sensory design and future scenarios of internal research and development of APDO product application comfort.

Together, these findings can have multiple applications, including:

- The improvement of APDO formulation across different product types for enhanced wetness and thermal comfort during application,
- The improved understanding of how consumer hygiene routines, specifically shaving and showering, may impact wetness perception during product application,
- The development of a continuous wetness perception assessment for a greater depth and understanding of the onset, development and decay in our perception to inform product design during contact. This can be translated into other perception outcome measures during product consumer testing, such as thermal sensation.

A schematic summary of the PhD findings can be seen in Figure 48.

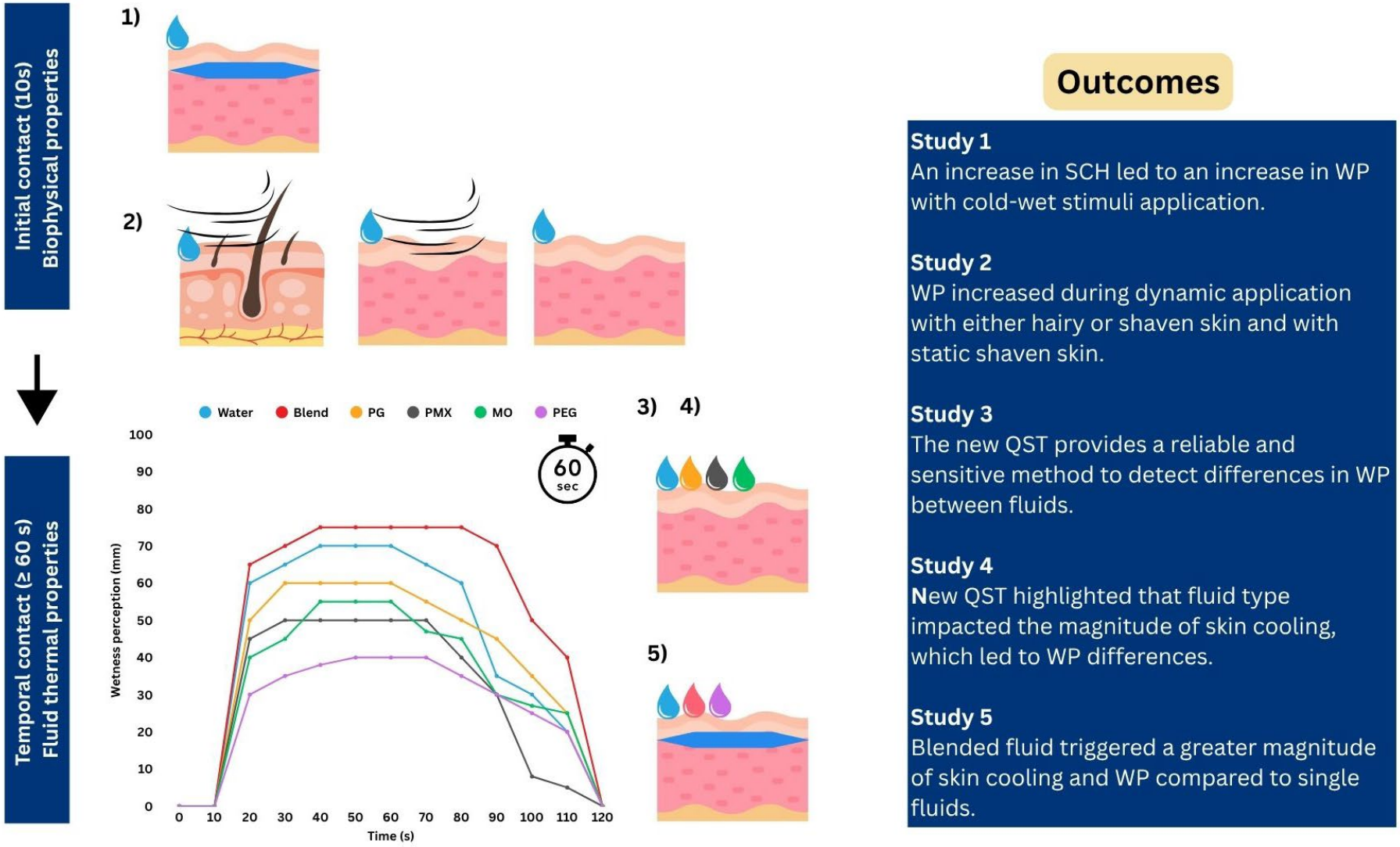

Figure 48. A summary of the PhD project key findings. *WP = wetness perception, QST = quantitative sensory test, SCH = stratum corneum hydration*.

Original Contributions to Knowledge and Applications of the Findings

Experimental Study 1:

Aim: Determine the mechanisms for wetness perception at the underarm during static external stimulus application and the role of SCH on wetness perception (Chapter 4).

- **Original Finding 1:** It was demonstrated that the mechanisms for wetness perception at different regions of the underarm were similar to those previously observed across other skin sites on the human body. Specifically, during short-duration (~10 s) contact with statically applied wet stimuli, with the same moisture content, cold-wet stimuli consistently induced wetter perceptions than warm and neutral wet ones (Filingeri et al., 2014b).
- **Original Finding 2:** It was observed that overhydration of the underarm's stratum corneum (~20 % increase) can lead to an increase in wetness perceptions upon contact with cold-wet stimuli only (~20 % increase).

  Fundamental Implications: These novel site-specific observations demonstrated that underarm wetness perception follows the same thermally driven principles as other skin regions and confirm that wetness is not sensed by dedicated hygroreceptors but instead emerges from the integration of thermal and tactile inputs. Furthermore, these findings highlighted the importance of the biophysical status of the skin, partly modulating the perceptual effects of local skin cooling on underarm wetness perception. This demonstrates that wetness perception is not only stimulus-dependent but also modulated by the biophysical state of the skin.

- **Applied Implications:** This has important applied implications for understanding "wet feel" upon initial APDO application. As such, if the product was cold, at least - 5 °C below skin temperature, then the consumer may experience the product as wetter during application compared to a product that is applied at or above skin temperature (≥ 34 °C). Additionally, during cold-wet applications, the wetness experienced may increase when the skin is overhydrated, such as after daily activities like exercise or a shower. Therefore, the timing of product application and temperature are important factors which could inform product design for improved thermal comfort.

Experimental Study 2:

Aim: Evaluate the role of hairiness on wetness perception during static and dynamic cold-wet stimuli application to the underarm (Chapter 5).

- **Original Finding 1:** Wetness perception was influenced by the mode of application and the biophysical properties of the skin site (i.e. hairy vs shaven). As such, during static cold-wet applications, wetness perception was ~20 % lower in magnitude under hairy compared to shaven skin conditions.
- **Original Finding 2:** The magnitude of wetness perception increased by approximately 20 % during dynamic compared with static applications under hairy conditions only. Despite this increase, wetness perception on hairy skin during dynamic application was not greater than that experienced during either static or dynamic stimulation of shaven skin. These findings extend previous work showing that wetness perception increases during dynamic compared to static stimulation at both hairy and glabrous skin sites (Filingeri et al., 2014b), by demonstrating that differences between hairy and shaven skin also influence this effect.
  Fundamental Implications: These results provide novel empirical evidence on the dual role that underarm hairs can play in modulating wetness perception, i.e. acting as “thermal insulators” under static wet stimulus interactions, and as “perception enhancers” under dynamic wet stimulus interactions. These new findings further expand our understanding of the thermal and tactile determinants of the “wet feel” resulting from contact with a cold-wet stimulus at the underarm.

- **Applied Implications:** These findings have important applied implications for APDO products. During static product contact, such as spray formulations settling on the underarm, hair may reduce the perception of wetness by limiting skin cooling, potentially improving perceived dryness. In contrast, during dynamic application (e.g. roll-on or gel), movement of the product across hairy skin may enhance wetness perception due to increased tactile and thermal interactions. This may also have sex-specific implications. Previous research has shown that roll-on and cream formulas are more commonly associated with female users, whereas stick and spray formulas tend to have a greater male association (Gámbaro et al., 2019). Therefore, optimising APDO formulation properties, such as cooling profile, drying time, and spreading behaviour, and considering the application method, may help minimise dynamic wet interactions, particularly on hairy skin, thereby improving perceived dryness and overall product comfort.

Experimental Study 3:

Aim: Explore a new quantitative sensory testing method to assess temporal changes in wetness perception with a range of external stimuli at the forearm (Chapter 6).

- **Original Finding 1:** Developed a new continuous wetness perception assessment, with skin temperature integration to measure temporal changes in wetness perception and concurrent skin temperature during extended contact (≥ 60 s) with a stimuli at the forearm.
  Fundamental Implications: This novel assessment provides a high-resolution time-dependent methodology to perform psychophysiological experiments on perceptual experiences, such as wetness, and incorporates the associated biophysical skin changes, resulting from external contact with a wet stimuli.

- **Original Finding 2:** Wetness perception has been characterised into four key features of the time-dependent trace, and further individual parameters within each key phase can be assessed for differences in wetness perception response based on the fluid application.
  Fundamental Implications: In comparison to our understanding of 'acute' wetness perception through previous studies (Filingeri et al., 2014a). The novel method goes beyond previous single time-point assessments by revealing four key phases during the development and decay of wetness upon stimulus application and removal in the temporal dynamics of local wetness perception, namely the *'onset of wetness', the 'magnitude of wetness', the 'decay in wetness' and the 'changes in wetness after peak'*. Furthermore, within those phases, 14 individual wetness perception parameters were captured, providing greater insights into time-dependent scenario-specific skin-moisture interactions.

- **Original Finding 3:** The new quantitative testing method is sensitive enough to discriminate differences in wetness perception during the application of different fluids varying in thermal conductivity and heat capacity properties.
  Fundamental Implications: Differences in wetness perception response characterised the performance of the measurement tool through repeated fluid applications, providing repeatability and reliability of the methodology. Additionally, the MDC was established for the wetness perception parameters, ensuring a critical approach when analysing the data, and confirming that differences between fluids were a function of a meaningful difference.

- **Applied Implications:** The innovation and translation of a novel QST method can be used during P&G consumer product testing to provide greater insight into the temporal dynamics of wetness perception and interindividual differences during the application and upon the removal of real-world APDO product testing.

Experimental Study 4:

Aim: Establish the role of a single-component fluid's thermal properties on skin cooling and consequently skin wetness perception during and after contact with a cold-wet stimulus at the underarm (Chapter 7).

- **Original Finding 1:** The newly developed QST method was successfully applied and refined to the underarm, demonstrating consistent wetness perception responses across the time-dependent curve, including the identified parameters and key perceptual phases.
  Fundamental Implications: The consistency of time-dependent wetness perception curves and identified parameters suggests that wetness perception follows a reproducible sensory processing pattern at the underarm and the forearm. This implies wetness is a temporally changing perception. This strengthens the confidence in the method's criterion validity, supporting its use in both experimental and applied research.

- **Original Finding 2:** Skin cooling rates during and after stimuli contact can be used to explain the differences in wetness perception experienced between fluid applications. The higher the thermal conductivity and heat capacity of the fluid, the greater the magnitude of skin cooling, which equates to a higher wetness perception.
  Fundamental Implications: This novel assessment has enhanced our understanding of the relationship between the skin temperature and wetness perception during the development and decay in perception at the underarm. This advances our understanding of wetness perception as a multisensory experience driven by heat transfer at the skin–fluid interface for thermal detection. The different rates and total magnitude of skin cooling have been identified as the key drivers in wetness differences, which directly link to the fluid's thermal properties (Bergmann Tiest and Kappers, 2009, Bergmann Tiest et al., 2012). As such, fluids with greater thermal conductivity (i.e. water; 0.6 W/m·K) had a greater magnitude of skin cooling (3.4 ± 0.4 °C) and consequent greatest wetness perceptions (74 ± 19 mm) at the underarm during contact. Therefore, changes in skin temperature during contact with different fluids could be utilised as the foundation to start building a model to predict the wetness they might experience based on measurable physical properties of a fluid.

- **Applied Implications:** This knowledge may impact future APDO fluid formulation choice to minimise application-induced wetness perceptions at the underarm for a range of products such as roll-ons, sprays and gels. This opens avenues for designing formulations that feel drier by limiting skin cooling, rather than altering moisture levels. These findings provide novel fundamental insights into the underarm's perceptual responses to wetness during extended contact (≥ 60 s) with varying fluids, known for their use in APDO formulation. This

could inform understanding of the determinants of wet feel and thermal comfort associated with the application of APDO products using this method as a tool to evaluate product-induced changes in wetness perception over time. The refinements to this methodology ensure it remains adaptable for P&G's consumer testing, with regular re-evaluation prior to use to reinforce that the data collection approach is appropriate for every new internal product study.

Experimental Study 5:

Aim: Investigate the effect of the blended fluid combination and the role of skin hydration on wetness perception at the underarm (Chapter 8).

- **Original Finding 1:** The model predictions using the thermal properties of the fluids and skin temperature for wetness perception response do not entirely align for the blended fluid, likely due to the fluid not responding as expected.

  Fundamental Implications: When fluids were blended, wetness perception did not align predictably with the combined thermal properties. Despite having lower thermal conductivity (0.3 W/m·K) than water, the blend produced the greatest skin cooling (5.2 ± 0.2 °C), indicating that wetness perception cannot be explained by thermal properties and skin temperature alone, although the magnitude of skin cooling remains a key driver in wetness differences. However, some ambiguity remains, as peak wetness perception for water in the current study (44 ± 21 mm) was lower than previously reported values (74 ± 19 mm), which is likely being driven by the bigger delta change in skin temperature. When the response data across the studies were combined and averaged, the wetness perception trace of the blend followed a pattern consistent with its thermal properties, similar to the fluids in Chapter 7 (Figure 49). This suggests that the observed variance may not reflect a unique effect of the blended formulation per se, but rather variability in the wetness response to fluid application, despite standardising the application protocol and controlling probe and fluid temperature across studies. These findings highlight the need for further work to refine experimental designs, isolate formulation-specific effects, and more precisely characterise the determinants of wetness perception.

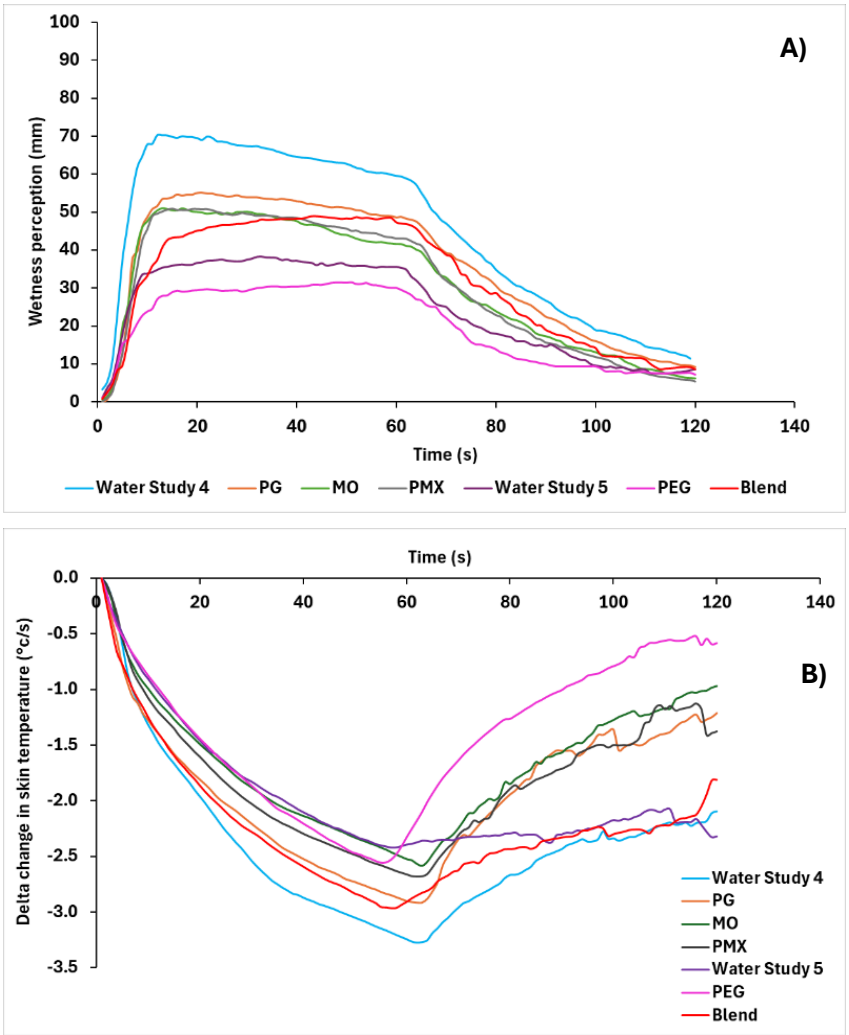

Figure 49. Presents continuous mean wetness perception A) and delta change in skin temperature B) combined responses during both contact and post-contact phases of our c-WPT in the experimental studies (Chapters 7 and 8), and in relation to each of the 7 fluids used. WaterS3 = water from study 4, propylene glycol = PG, mineral oil = MO, dimethicone = PMX, WaterS4 = water from study 5, polyethene glycol = PEG, and 50/50 water/PEG = blend.

- **Original Finding 2:** During extended contact (≥ 60 s) with cold-wet stimuli, fluid type is a more important factor that will impact wetness perception, rather than biophysical properties (i.e. overhydration) of the skin.

  Fundamental Implications: The fluids, whether single-component or blended, behaved similarly regarding their skin cooling and wetness perception experienced, before and after overhydrating the skin. Therefore, fluid type is more likely to impact wetness perception rather than differences in the biophysical properties of the skin, this implies that timings of APDO application are less important compared to the formulation of the product.

Furthermore, the lack of differences in wetness perception with overhydrated skin, compared to Chapter 4 could be linked to the robustness of the newly established method and criteria for the MDC (8 mm) for differences in wetness response. Highlighting the importance of establishing a detection threshold for error to ensure a real, meaningful change in results.

- **Applied Implications:** These findings have important applied implications for APDO formulation and performance optimisation. Specifically, the wetness perception response to blended formulations cannot be reliably predicted based solely on the thermal properties of their individual components, indicating that formulation behaviour on the skin is more complex than expected. This emphasises the importance of empirically evaluating complete product formulations, rather than assuming effects of ingredients, to ensure they minimise skin cooling and perceived wetness. Furthermore, the observation that fluid type had a greater influence on wetness perception than the biophysical state of the skin during prolonged contact suggests that APDO formulation characteristics—such as volatility and thermal behaviour—are more critical determinants of perceived dryness than the variations in skin hydration and timing of application. Therefore, prioritising formulation strategies that reduce the magnitude and duration of skin cooling will be key to improving perceived dryness and overall product thermal comfort.

Wider Applied Implications:

Beyond antiperspirant and deodorant development, this work has broader implications for understanding and managing human comfort in any context involving skin–fluid interactions and thermally driven sensory experiences. By establishing skin cooling as a primary determinant of perceived wetness and demonstrating that wetness perception unfolds as a time-dependent process, this research informs wider fields concerned with thermal comfort, material–skin interactions, and multisensory perception. The findings could be used to inform the design and evaluation of clothing and wearable textiles, particularly moisture-managing fabrics, where perceived wetness and cooling can influence comfort and performance. Similarly, the insights gained into the role of fluid thermal properties and formulation complexity may inform the development of topical products such as cosmetics, sunscreens and wound-care dressings, where application feel, and thermal comfort influence user acceptance and adherence. Methodologically, the novel QST approach offers a transferable framework for assessing temporally evolving perceptual responses across skin sites, enabling more ecologically valid investigations of touch, temperature, and moisture-related sensations.

9.1.1 P&G Impact Statement

In the past 3 years, Jade Ward, a Master's Science candidate from the University of Southampton's Thermosense Lab, collaborated with P&G Personal Care Deodorants to define the physiological and perceptual mechanisms of skin wetness at the underarm. In Jade's research, she conducted several studies to understand: (1) Skin hydration and local wetness perception in a pilot study, where a new, in vivo method was explored, (2) Wetness perception with and without hair and with static and dynamic application, (3) Wetness perception of 4 common fluids used in personal care products, (4) Wetness perception and stratum corneum hydration for 2 common fluids used in personal care products, and a blend.

During her project, Jade continuously refined her method to gain better data insights from study to study. For example, in a later study, Jade had all participants begin early in the day, as we know that skin hydration can change throughout the day. She also took a baseline Corneometer reading after an acclimation time, which provided an opportunity to normalise data. In her final year, Jade also travelled to P&G to present the outcomes of her 4 studies, which was well-received by our Personal Care department.

There are several insights from Jade's research work that we are considering for future studies, including:

(1) Reapplication of the continuous visual analogue scale to assess time-dependent changes in wetness perception,

(2) Leveraging the thermal conductivity of a single fluid to predict wetness perception through the level of cooling received during fluid contact,

(3) The impact of mixed fluid combinations on thermal properties and wetness perception,

(4) Differences in wetness perception observed on hairy and non-hairy underarms during static applications (e.g. deodorant sprays),

(5) Differences in wetness perception for application post-shower vs. not after a shower (e.g. products with a higher magnitude of skin cooling could feel wetter longer when not applied after a shower).

Consumer wetness perception of products continues to be a trial barrier for adopting forms that may be perceived to feel wet and wet longer, e.g. clear gels, deodorant sprays. The research revealed new methods to better understand wetness perception, factors for fluid selection, and key consumer considerations linked to evaluation.

9.2 Future Research Directions

The current research has expanded our knowledge on wetness perception during or after modulating skin biophysical and fluid thermal properties for external stimuli application. The findings of these studies have highlighted a series of limitations and opened new directions for future research questions to expand our understanding of the mechanisms that underpin the perception of skin wetness.

Considerable inter- and intrasubject variability was observed in wetness perception responses across repeated fluid applications, with the underlying cause remaining unclear. Although relative differences between fluids were consistent, absolute response magnitudes varied within individuals, suggesting differences in sensory baselines and perceptual scaling strategies. Preliminary data scrutiny indicated potential “responder” categories (high, middle, low), yet fluid-related differences were still evident within each individual’s reporting range. The mechanisms driving this variability are unknown but may relate to factors such as habitual APDO use or product preference, which could shape sensory expectations and perceptual responses (i.e. spray feeling drier vs gel feeling wetter). Future research should combine controlled psychophysical testing with APDO behavioural and usage profiling in larger cohorts to differentiate physiological, perceptual, and experiential influences on wetness perception, thereby strengthening mechanistic understanding and enabling more targeted consumer applications.

The experimental work in this thesis focused on the mechanism of wetness perception in young healthy individuals. Whilst relevant to gain an initial insight into underarm wetness sensing during single spot check and temporal changes for healthy controls, the exclusion criteria provide a limitation to further expanding our knowledge for individuals who may have altered sudomotor function, such as neurological disorders like autism and attention-deficit hyperactivity disorder. A population of individuals who experience daily skin-moisturiser interaction, such as applying an APDO. It is generally understood that individuals with a neurological disorder may be hyper- or hyposensitive to external stimuli such as thermal sensation (Watts et al., 2016). In some cases, this hyposensitivity could lead to safety concerns when touching objects of noxious temperatures or impacting clothing choice for extreme weather (Nader et al., 2004). The atypical function of the thermosensory pathway may be linked to the altered perception (Dunn, 1997). Yet, there is no evidence on how this pathway may impact the sensitivity to wetness perception. Future studies should therefore recruit individuals with neurological disorders to investigate thermal sensitivity and wetness perception during a range of external stimulus applications.

At the start of this PhD partnership with P&G, it was discussed whether to investigate the interaction of an external stimulus for skin wetness response to inform APDO application or to investigate the 'sweat event' to inform internal skin-moisture interactions for APDO design. As it is clear from this thesis, the research did not focus on the sweat event, and hence, there is an opportunity to investigate this further. Much of the current knowledge on wetness perception has focused on the external evaluation (Merrick et al., 2021, Valenza et al., 2019, Ward et al., 2025, Filingeri et al., 2014a). Whereas there is limited understanding of the wetness perception when the moisture source is internal, such as sweat. Previous literature has investigated skin-moisture interaction via sweat production to understand how, in the absence of skin cooling, the tactile cues modulated the perception of sweat-induced skin wetness whilst wearing either tight-fit or loose-fit clothing (Filingeri et al., 2015c). Yet, this was investigated across the whole body, whereby the underarm would be the focus here as this has the most applicability for P&G. With tactile cues being a driver in wetness perception when skin cooling is limited, it would be interesting to investigate this further by stimulating the onset of sweating at the underarm and isolating the thermal and tactile cues to identify the key mechanisms and threshold detection for sweat-induced skin wetness.

Conclusion

To conclude, this PhD project provides novel fundamental insight into the mechanisms of wetness perception at the underarm with a focus on the role of biophysical (hair and skin hydration) and fluid thermal properties during contact with an external wet stimulus. The research offers the first continuous QST method for wetness assessment, detailing the temporally dynamic characteristics of this perception and providing a greater understanding of the role of skin cooling for wetness detection, specifically for fluids ranging in their thermal properties. These findings fill the critical gaps in wetness perception during external wet-stimulus contact and generate empirical evidence of direct relevance for improving APDO design for application, regarding the role of hair, SCH and fluid type on the modulation of wetness at the underarm to inform user-centred product development. Collectively, this work extended the current knowledge of the wetness perception framework by advancing the scientific understanding of physiological and perceptual mechanisms and developing a rigorous high-resolution method for future investigations. This enables more informed and refined research designs for scenario-specific skin-moisture interactions for improved thermal comfort across the range of APDO product applications.

Appendix A Ethical Approval

Studies 1 and 2 (Chapter 4 and Chapter 5)

ERGO II – Ethics and Research Governance Online https://www.ergo2.soton.ac.uk

Submission ID: 73017.A2
Submission Title: The effects of different skin hydration levels on wetness perception (Amendment 2)
Submitter Name: Davide Filingeri

Your submission has now been approved by the Faculty Ethics Committee. You can begin your research unless you are still awaiting any other reviews or conditions of your approval.

Studies 3, 4 and 5 (Chapter 6 - 8)

ERGO II – Ethics and Research Governance Online https://www.ergo2.soton.ac.uk

Submission ID: 81776
Submission Title: How does different liquids with a range of thermal diffusivity properties impact the rate of change in skin temperature, and consequently, local skin wetness perception
Submitter Name: Jade Ward

Your submission has now been approved by the Faculty Ethics Committee. You can begin your research unless you are still awaiting any other reviews or conditions of your approval.

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