

**Cosmetic research study:
bridging material science with social
inquiry**

By

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Statement of originality

I, Gabriela Daniels (student ID: 22050186) declare that this is an original piece of work. I have acknowledged all sources and citations. No sections of this thesis have been plagiarised.

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I declare that no part of this submission has been generated by AI software.

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Abstract

This PhD thesis advances an interdisciplinary framework for cosmetic research by bridging materials science methodologies for hair investigation with social scientific inquiry into lived experience, identity, and wellbeing. While human hair has been extensively investigated as a keratin-based composite fibre with measurable mechanical and physicochemical properties of relevance to cosmetic products, human-centred investigations have been mostly assigned to the domains of consumer and marketing research. This body of work addresses this methodological and conceptual gap by integrating hair fibre and assembly behaviour research with studies of personal goals and perception of hair management within a unified research trajectory.

The thesis comprises six peer-reviewed publications (2018–2024) that collectively demonstrate a progression from established combing and image-based laboratory methodologies towards interdisciplinary, human-centred research designs. Early studies critically examine prevailing assumptions in hair combing and tensile testing, with subsequent work focused on artificial intelligence and computer vision techniques to assess hair assembly features, such as volume and alignment. A critical review then reports the variability of human hair from composition, geometrical and technical perspectives. The later publications extend the research scope to curlier hair types through mixed-methods social science approaches. The final publication is distinct and intentionally provocative. Rather than focusing on testing method development, it challenges dominant assumptions about beauty, vision and consumption that underpin much of the existing scholarship.

Synthesising insights from these studies, the thesis moves beyond individual methodological contributions to articulate and propose an interdisciplinary research framework for hair and cosmetic science more broadly. This framework inverts the conventional linear model of research progression, from fibre to assembly to presumed consumer benefit, by positioning lived experience at the generative starting point that guides material investigation. It outlines both theoretical and methodological principles for integrating objective material measurements with socially situated human data, thereby strengthening scientific relevance, inclusivity and wellbeing-oriented innovation.

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Introduction

Alongside the face and body, human hair forms a visible marker of individuality across the lifespan. Symbolic associations between hair, health, strength and fertility have been recognised for centuries, appearing in mythology, religious texts and the arts. For example, in the Bible, Samson's strength is tied to his long hair, and historically, elaborate wigs have symbolised status and wealth (Leach, 1958; Synnott, 1987; Broida, 2010; Lowe, 2016, pp. 3-4). While elements of these traditional symbolisms persist today, modern interpretations, both scholarly and societal, are shaped by social, political and cultural forces that have increasingly emphasised and celebrated hair diversity as a source of personal empowerment and wellbeing. Given the capacity of hair to act as a marker of identity, scientific research will be enriched by combining studies of its material properties with those of the lived human experience. This body of work represents a novel contribution towards this objective and introduces an interdisciplinary methodology through which future cosmetic research of this nature can be systematically advanced.

From a biological perspective, the hair fibre is an appendage of the human skin. Its formation and cyclical growth have been investigated extensively to elucidate the underlying regulation processes and to inform the modulation of healthy hair growth or therapeutic interventions (Messenger, 1993; Buffoli *et al.*, 2013; Trüeb, 2020, pp. 17-35). The hair fibre chemical composition, morphology, and physical behaviour are of relevance beyond the field of skin biology and health. Within scientific disciplines such as cosmetic science, forensics, and anthropology, human hair is researched for its material properties and its interactions with environmental factors, such as temperature, solar radiation, water and hair products, with the aim of understanding its functional performance.

As a composite protein-based fibre with a complex hierarchical structure, hair has been frequently investigated by applying methodologies adapted from textile science. Insights from wool research, in particular, have guided the mechanical and thermodynamic analyses of hair by offering a framework for interpreting results in relation to the fibre's micro- and macrostructural characteristics (Robbins and Kelly, 1970 pp. 891-895; Feughelman, 1997; Wortmann, 2009a, pp.108-145). The scientific progress achieved by adapting these methods to hair has, so far, greatly enriched the understanding of hair as a material but there remains a gap between this fundamental knowledge and the applications of it to more consumer-relevant research.

From a cosmetic perspective, the properties of individual fibres are important for understanding how they interact within the head of hair, particularly in relation to daily grooming routines and environmental changes (Marsh *et al.*, 2015, pp. 45-52). For

example, the way fibres respond to humidity fluctuations can influence the effectiveness of cosmetic treatments in the context of everyday hair management and styling, thus making it a key focus of cosmetic research (Martiny, 2002; Yu *et al.*, 2016; Uto *et al.*, 2024). Whilst knowledge of the cosmetics and hair interactions has been expanding over the years, the majority of studies have been based on experimentation with straight hair fibres. Over time, this methodological gap has been recognised, with scientific, business, and consumer voices calling for expanded research to capture the full diversity of human hair (Cloete *et al.*, 2019; Uto *et al.*, 2024; Scott, 2025).

Recently, Genome-wide association studies have demonstrated that genetic factors play a central role in determining the variability of human hair in terms of its morphology, colour and growth characteristics, with global demographic changes contributing to increasing hair diversity (Liu, F. *et al.*, 2018; Morgan *et al.*, 2018; Ho *et al.*, 2020; Lona-Durazo *et al.*, 2021). These developments further highlight the need for new techniques capable of capturing and quantifying the fundamental physical and morphological characteristics of a wide range of hair types. However, methodological limitations in hair fibre and assembly research have, in part, contributed to this historic predominance of straight hair experimentation. These limitations arise from the reduced repeatability and reproducibility when most instruments and the related testing methods are applied to curlier hair types. They are further compounded by the restricted availability of hair samples that represent the full spectrum of curl patterns, which constrains the feasibility of such studies. Addressing these limitations calls for innovative methodological thinking, which this thesis offers via the analysis and synthesis of the outcomes of the separate publications that it covers.

Beyond technical refinement, methodological advances should strengthen the research relevance to the human context of hair. Methodologies that fail to incorporate these factors risk oversimplifying the relationships between fibre-level properties, assembly behaviour and the lived experience of hair. Closing this methodological gap also has implications that extend beyond the experimental laboratory domain. It has the potential to advance the field of cosmetic science more broadly by supporting inclusive product innovation, and to enable more holistic and personalised outcomes that reflect the cultural significance of hair and promote wellbeing.

Within this historical context, hair research falls into three main domains that methodologically complement and inform each other: fibre science, assembly behaviour and the lived experience of hair (Figure 1). The first two domains would be commonly combined into a study design via a linear trajectory. Experimentation typically begins with the fibre, followed by assembly level assessments, with references in the discussion and

conclusion to the presumed benefits for the human experience. This sequential approach provides robust scientific insights, but it could be somewhat limited in reflecting the personal, aesthetic, and experiential dimensions that shape individuals' hair practices. A new, alternative approach, presented by this body of work, is to invert this sequence, starting from human experience research and working backward to assembly and fibre level analyses. This reorientation places the definition of meaningful benefits as the guiding driver of the fibre and assembly experimentation, so that research outcomes are both scientifically robust and consumer relevant.

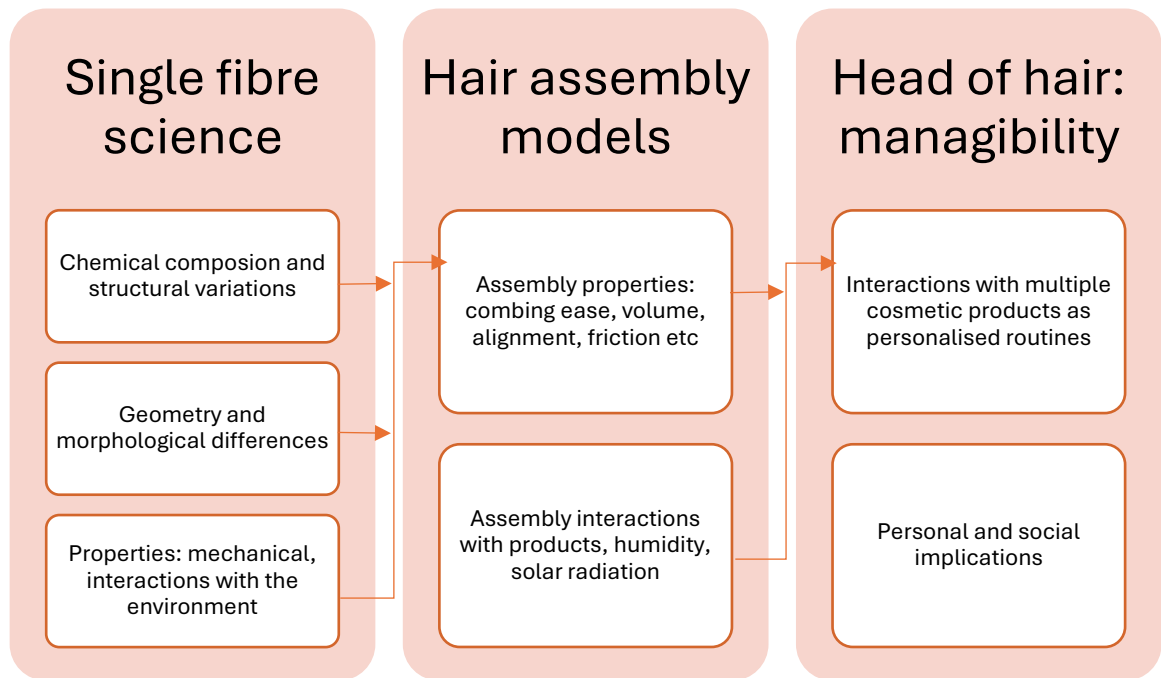


Figure 1. Domains of hair research, showing the integration and progression of knowledge and research from fibre structure, through cosmetic functions and personal experience.

Recent advances in artificial intelligence (AI) driven methods for complex data acquisition, analysis and modelling offer further promising opportunities. Building on the successes of consumer-focused personalisation in nutrition, exercise and, more recently, skin and colour cosmetics, it has been suggested that AI could accelerate innovations in personalised hair care (Pickering and Kiely, 2019; Zanker *et al.*, 2019; Tsolakidis *et al.*, 2024). However, more fibre and assembly level data reflecting all hair variations is needed to achieve this goal. A shortage of high-quality, publicly available training datasets means that most AI-driven innovation currently remains industry-led, limiting transparency and cross-sector collaboration. This imbalance calls for more academic research aimed at generating standardised datasets and developing independent

analytical methods. This thesis offers a specific instance of such research, thus situating itself within the broader effort to develop scientifically rigorous datasets for AI applications to cosmetic research. These efforts will ensure that innovation in hair science is guided not only by commercial priorities, but also by broader scientific evidence.

Cosmetic-focused research has sought to identify what constitutes “beautiful” skin and hair as the ultimate goal of product usage. For example, skin texture parameters such as good hydration level, absence of visible lesions, light diffusion, facial feature adaptations using makeup and hair fibre elasticity and flexibility have all been reported to impact positively on the subjective quality of skin and hair (Puccetti *et al.* 2011; Etcoff *et al.*, 2011; Ezure *et al.*, 2019; Valenzuela *et al.*, 2025). Other studies have positioned the strive for beauty alongside more holistic wellbeing, fitness and selfcare (Uhlmann *et al.*, 2018; Tiggemann and Zaccardo, 2018; De Valle *et al.*, 2021; Wood, 2024). Thus, beyond the basic utilitarian functionality, the routines and consumption of haircare products and cosmetics more broadly, are both shaped by and contribute to multifaceted lived experiences connected to personal needs, social identities and wellbeing. Research in social and material sciences has advanced significantly towards better understanding these phenomena and serving the needs of diverse users. However, these disciplines follow largely distinct methodological and epistemological trajectories, despite the clear potential for cross-fertilisation. Bridging this disciplinary separation, as demonstrated in this PhD thesis and its constituent research studies, offers opportunities to learn more about how the materiality and the human experience of hair and cosmetics can influence each other for better and more wide-reaching effects.

PhD thesis: aim and objectives

Aim

This body of work aims to articulate the rationale and the benefits of bridging the materials science research relevant to hair and cosmetic product development, and social sciences scholarship which explores the motivations and social context that define engagement with cosmetics. A further and related aim is to progress this research towards an interdisciplinary framework for methodological and theoretical expansion of the relevant subject fields.

Objectives

- i) To examine and contribute to the development of hair research methodologies via the explicit integration of elements from all three domains of hair research (fibre science, assembly behaviour and lived experience).
- ii) To outline an interdisciplinary research framework that explicitly links the study of hair as a complex material with its behavioural and social contexts.
- iii) To contribute to the development of an interdisciplinary field of knowledge that connects scientific and social inquiry in order to study motivation and engagement with cosmetics from a wellbeing perspective.

Synthesis of the published work

This PhD thesis presents six peer-reviewed articles, published between 2018 and 2024, responding to the above research aims and objectives in the following ways:

- Methodologically, the work illustrates a progression from laboratory-based hair testing, incorporating elements of consumer insights, toward human-centred research integrating material science with social inquiry.
- The research domain expands from hair fibre studies, toward human motivation for cosmetic use more broadly.

Collectively, the first two articles represent the start of the research journey, as they explore established hair assembly characteristics, such as combing ease, volume, and alignment of straight hair, also drawing on a theoretical hair management and styling framework considered still valid to date (Robbins and Scott, 1978). They further the understanding and interpretations of hair-testing methodologies by highlighting the potential value of integrating human data to support and interpret the findings of *ex vivo* hair tests. In the consumer hair-combing article, human-centred data inform the experimental design and support the critical interpretation of the results (New *et al.*, 2018). The article's conclusion challenges common assumptions in hair testing at the time that the mechanical loads and the damage incurred in a single fibre tests represent typical hair damage under normal hair combing conditions. From materials science point of view, this article is focused on straight hair type only, albeit some fibre variability is introduced in the experimentation. In the following "*proof of concept*" study, human visual assessment and AI-based hair image analyses are compared (Daniels *et al.*, 2021). The research identifies the trade-offs between visual hair assembly qualities such as volume, alignment, and flyaway, illustrates the application of computer-vision based AI, and highlights the complexities of sensory assessment. The subject of research remains straight hair and conditioning cosmetic treatments, but the AI-based method for assessing key hair visual characteristics is novel. In summary, these two studies treat combing, volume, alignment and flyaway as purely technical measures situated in hair fibre and assembly research domains, whilst seeking to improve their relevance to lived hair experiences by drawing on behavioural and sensory data.

The third article discussed in this thesis, a critical review, serves as a theoretical bridge for broadening the focus of research from straight to more diverse hair types (Daniels *et al.*, 2022). This review presents and critically analyses existing published data on human hair differences from a comprehensive scientific perspective. It also applies a critical lens

and identifies gaps in method reporting in the literature. The article argues that unifying the research on single fibre with related assembly property under a consistent framework, based on robust methodologies, enriches material hair knowledge and addresses more effectively hair diversity.

The following two articles are interrelated and focus on curlier hair types, which were identified in the critical review to have received comparatively less attention in the published literature. This research project effectively applies social science methods to generate a human-centred taxonomy for exploring a wide range of hair-related personal data: hair goals, hair esteem, typical haircare processes and practices, and related product preferences (Daniels and Heitmayer, 2024a, 2024b). Together, the articles demonstrate the potential of systematic research into human needs and behaviour to generate novel and effective testing methods and to support frameworks for haircare personalisation. A cyclical, mixed-method, sequential study design underpins both studies, providing a structured pathway for iterative development of the final research outcome. The resulting measurement instrument captures not only hair characteristics but it also incorporates measures of individuals' hair goals and behaviours, as well as an indicator of hair-related esteem. This novel research approach bridges materials and social sciences at methodological level. From fibre-science perspective, it is methodologically rooted in the head-of-hair manageability concepts, whilst simultaneously being informed by and aimed at informing method developments in fibre and assembly research. From social enquiry perspective, it draws on the mixed-methods research framework which combines both qualitative and quantitative methodologies to capture simultaneously breadth and depth of data and support more nuanced conclusions.

The final publication establishes the intersections between cosmetic research and social science at a theoretical level and situates its findings accordingly. It focuses on the personal and social significance of social disability, aesthetics, and beauty and multi-sensorial experiences by examining video material generated by a unique group of cosmetic users – Blind and Partially Sighted (BPS) makeup vloggers (Daniels and Khadaroo, 2024). Thus, albeit in a different context, the article continues with the theme of inclusive and diverse consumer-centred research. Building on the author's experience from the hair taxonomy research articles, this work is grounded in qualitative research methodologies. Qualitative research is not typically regarded as directly applicable to investigations in material science; however, this article presents an approach to data collection and analysis that may prove valuable in researching hair and the functional properties of cosmetic products. The article also brings attention to the social responsibility that researchers across different fields, industry professionals, and other

stakeholders must uphold to ensure that cosmetic products, and beauty practices more broadly, are inclusive and have a positive impact on wellbeing. The article also challenges a substantial body of research identifying beautifying practices as largely harmful by imposing unrealistic standards and encouraging consumerism, whilst suggesting a more nuanced interpretation of motivations, and of the perceived benefits or harms. Finally, the work was included in this thesis to raise the visibility of some consumer groups and encourage further academic and industry research. Hence, this publication responds to the aim of the PhD thesis in a different way, demonstrating the potential of pushing the research boundaries, both methodologically and cross-subject.

The individual contributions of each of the above publications to the field of cosmetic research and to the collective body of work are outlined at the end of each article summary. The impact of each article is also further iterated in relation to research citations, industry collaborations, cultural relevance, and the authors' research-led teaching practice. Holistically, the collective body of work presented here contributes to cosmetic research in two major ways: through methodological development and by promoting interdisciplinary research and knowledge development, with a focus on cosmetics efficacy and wellbeing. Additionally, its contribution extends to social research fields that engage with beauty and aesthetics, such as media and marketing research, gerontology, and cultural studies.

Collaborative working

Each project was designed as a collaboration with researchers from a range of disciplines, including sensory science, computer vision and AI, social psychology and hair science. Fully signed CRediT statements from all co-authors of each publication have been provided in the submission package for the purpose of transparency and in accordance with best practice (Allen *et al.*, 2019). The author's principal contribution to all collaborations can be summed up as follows: i) identifying the overarching research gap at the intersections of the different disciplines and cosmetic research (*conceptualisation*); ii) reaching out and forming the collaborative team and leading the overall direction of the research within the broader field of cosmetic and hair studies (*supervision*); iii) purposefully developing and applying interdisciplinary methodologies (*methodology and formal analysis*). With the exception of the first publication, the author also developed the original draft, submitted the articles for peer review (*writing – original draft*) and was responsible for actioning and responding to the reviewers and submitting the revisions (*writing – review & editing*).

Interdisciplinary PhD research teams bridging STEM and social sciences have potential to bring solutions to complex problems but have also been reported to face challenges such as balancing the breadth and depth across disciplines, ensuring methodological justification and agreeing appropriate academic language (Vanstone *et al.*, 2013). These challenges were largely of relevance to the research comprising this PhD thesis but were successfully addressed as evidenced by each article undergoing rigorous peer review and being published in a discipline-specific journal. Beyond their academic contributions to methodology development and subject knowledge, the publications also collectively respond to questions and challenges faced by the cosmetic industry, the research community and broader audiences, thus illustrating one of the principal strengths of interdisciplinary research.

Literature review

Human hair fundamentals: chemistry and structure

Hair is composed of keratinised proteins with two distinct conformational structures: α -helices and β -sheets (Feughelman, 1959). Used as an umbrella term, keratin(s) are the building blocks of mammalian fibres, nails, and horn. They are highly crosslinked and organised at several hierarchical levels, thus creating a strong composite fibre structure. The morphology of the various fibres, human hair, wool and others, has a common structural organisation, comprising a core, the cortex, surrounded by layers of overlapping flat cuticle cells providing protection. A third component, the medulla, consisting of empty vacuoles and some proteins, is present in coarse fibres, including some human fibres. Between species, fibres are differentiated by their cross-sectional area, the number of cuticle layers, the cuticle cells' thickness and the degree of overlap (Wortmann, 2009).

The helically structured hair proteins are organised into groups of thirty-two chains called intermediate filaments (IFs). The surrounding β -sheets are known as keratin-associated proteins (KAPs) and are characterised by their high sulphur content (Hiltehaus-Bong and Zahn, 1987). A higher-order structure, named macrofibrils, has been identified. These represent larger aggregates of IFs and their surrounding KAPs and are observable with modern imaging techniques such as transmission electron microscopy, tomography and atomic force microscopy (Franbourg *et al.*, 2003; Bryson *et al.*, 2008; McMullen and Zhang, 2020). The fundamental protein composition of human hair and the above structural hierarchy are considered largely identical across hairs of different shapes and curl levels (Franbourg *et al.*, 2003).

The complex protein structures described above are stabilised by inter- and intramolecular bonds, which are of specific interest in the materials science context, including cosmetics. Hydrogen bonds between the carbonyl oxygen of an amino acid and the amide hydrogen of another, four places along in the peptide chain, stabilise the α -helical protein structure (Swift, 1997, pp.22-23). Hydrogen bonds between the amino acid residues of the KAPs which contain hydroxyl groups are also common. Electrostatic bonds between oppositely charged amino acid residues, also referred to as salt bridges, are present too. However, most significant for the hair's overall shape are the disulfide bonds, formed as a result of oxidation of thiol groups of two cysteine molecules in the process of fibre formation in the hair follicle (Hiltehaus-Bong and Zahn, 1987). The resulting amino acid, cystine, contains the disulfide bridge and is credited with providing the permanence of hair structure and tensile properties (Swift, 1997, p.9). Hydrophobic bonds between hydrophobic amino acid residues are also present, specifically between

the two-strand coiled coils within the IFs (Swift, 1997, p.28). Hair tensile experiments are a valuable tool for exploring the relative significance of the different bonds, with experiments in the wet state being most informative of the status of disulfide bonds due to the disruption of hydrogen and electrostatic bonds by the water. A recent review of literature related to the different bonds present in keratins concludes that disulfide bonds in different locations are of varied significance to the hair's structural integrity and respond differently to mechanical and chemical interventions (Breakspear *et al.*, 2024a). The authors go further to suggest that disulfide bonds between IFs and KAPs are of strategic importance for the hair shape and mechanical properties and that broken disulfide bonds leading to the generation of cysteic acid residues increase the presence of hydrogen bonding in dry hair.

Human hair exhibits a typical fibre's hierarchical morphological structure consisting of the cuticle, cortex and medulla (Robbins, 2012, p. 43). The cuticle comprises five to ten layers of overlapping cells and serves as a primary barrier against chemical and mechanical damage (Koch *et al.*, 2019). At the molecular level, cuticle cells are predominantly composed of highly cross-linked KAPs with some contribution from IFs, collectively imparting surface hydrophobicity. The cortex cells comprise approximately 75% of the hair shaft's cross-sectional area (Swift, 1997; p.49). The cortical cells are filled with the macrofibrils, the structure of which was outlined in the preceding paragraph and also contain remnants of cell nuclei and the melanosomes, giving the hair its colour (Swift, 1997, pp.56-57). The human hair exhibit two predominant cortical cell types, differentiated by macrofibril size, packing density and the orientation of the IFs. Ortho-cortical cells are circular, loosely packed, and contain a higher proportion of matrix proteins with helically arranged IFs. The para-cortex cells are characterised by larger, more densely fused macrofibrils, with IFs arranged parallel to the fibre axis (Bryson *et al.*, 2008; Wortmann *et al.*, 2019). In straight hair, these cell types are distributed uniformly across the cortex, whereas in curly hair, a bilateral distribution is typically observed, correlating with the asymmetry responsible for curvature (Wortmann *et al.*, 2019). This structural differentiation supports the current understanding that fibre curl results from internal asymmetries in cortical composition and organisation.

The Cell Membrane Complex (CMC) of hair consists of two lipid β -layers, each anchored to adjacent cell membranes, with a central δ -layer of structural proteins (Swift, 1997, pp. 46–47; Robbins, 2012, pp. 135–136). Structural differences between cortical and cuticular CMCs have been observed: the fatty acid monolayers in the cortex are largely unbound to the cell membrane proteins, whereas those in the cuticle are more extensively covalently bonded (Robbins, 2012, pp. 77–79). Of particular relevance to fibre hydrophobicity is the monolayer of 18-methyleicosanoic acid (18-MEA), covalently

bonded to the outer protein layers of each cuticle cell, which acts as a barrier to moisture ingress (Robbins, 2012, p. 138). The presence of water in the fibre disrupts hydrogen and electrostatic bonds and has been shown to reduce tensile strength and increase fatigue failure probability; hence, from a scientific perspective, hair is most vulnerable when wet (Evans, 2013a).

Morphological and structural comparisons of wool and human hair fibres are commonly reported. At scale level, fine wool fibres are reported to have a mean diameter of approximately 20-25 microns (Skals *et al.*, 2018; p.163; Andrews *et al.*, 1987; p.25; Bradbury, 1977), significantly smaller than the lower values than those of the human hair diameter ranging from 70 microns to >100 microns (Loussouarn, *et al.*, 2016, p.149). Another significant difference is the cuticle structure, which, in wool, is a single cell thick (Bradbury and Leeder, 1969; Roggers, 2019). Despite other morphological differences, both wool and human hair exhibit comparable cortical architecture, characterised by the presence of para- and ortho-cortical cells and their associated fibrillar substructures. (Bradbury, 1976). But, in wool, their bilateral distribution is well evidenced as a reason for the fibre crimp (Wortmann *et al.*, 2019). Amino acid analysis highlights specific differences in human hair and primates from other animals, including wool, most significantly in the high cystine content (reported as ½ Cys), thus suggesting higher cross-linking (Table 1). The quantities of the basic amino acids (His, Lys and Arg) are similar,

Table 1. Comparative keratin composition of fibres from different origins. Quantities are expressed as %w/w dry hair mass. Adapted from Block (1939, p.183)

	Nitrogen	Sulfur	1/2 Cys	Tyr	Trp	His	Lys	Arg
Human hair	15.4	5	15.5	3	0.7	0.6	2.5	8.01
Chimpanzee hair	16.7	4.3	15.5	3.3	1.4	0.6	2	8.11
Goat hair	16.2	3.1	8.9	3	0.9	0.7	3.2	8.1
Cow	15.3	3.7	13.4	3.3	1.5	0.7	2	7.51
Lamb wool	15.4	3.6	13.1	4.5	0.7	0.7	2.5	8.7

Other authors have reported the following qualities of acidic amino acids expressed in μ moles per gram dry material: merino wool: Glu - 1049, 1/2 Cys - 922, Asp - 560 (Bradbury and Chapman, 1965, p. 356); human hair: Glu – 1030, ½ Cys - 1509, Asp - 437 (Robbins, 2012, p.117)*.

*Three-letter amino-acid codes: ½ Cys=cystine, His=histidine, Lys=Lysine, Arg=Arginine, Tyr = Tyrosine, Trp=Tryptophane, Glu=Glutamic acid, Asp=Aspartic acid.

Human hair classification

Variations of hair fibre at macroscopic level represent characteristics defining the different human phenotypes, particularly in terms of fibre geometry and curl pattern. A comprehensive global population-based study identified eight distinct curl types, ranging from completely straight to tightly coiled fibres, and proposed a quantitative method for curl classification based on single-fibre measurements (Loussouarn *et al.*, 2007). To date, this remains the only scientifically validated system for categorising hair curl morphology. However, in hairdressing training and social media, a simpler classification is commonly used, based on four main curl types (Gittens, 2014, p.25).

Scientific understanding of how intrinsic hair structure gives rise to observable fibre shape and curl is also advancing. It is now recognised that hair shape and curl are largely determined within the follicle, where early structural asymmetries influence fibre formation (Thibaut *et al.*, 2004; Bertolini *et al.*, 2018; Richena *et al.*, 2021).

Mechanical hair fibre testing

A common method used to characterise the mechanical properties of hair fibres is tensile testing under controlled humidity conditions. This process generates a stress–strain curve, beginning with an initial linear region in which elongation (strain) is directly proportional to the applied force (normally converted to stress by dividing it by the estimated cross sectional fibre area). This is followed by a yield point and a plateau region, marked by rapid elongation at a relatively constant force, and a subsequent second linear region that leads to fibre rupture. The elastic modulus, or Young’s modulus, is calculated as the slope of the initial linear portion of the curve and reflects the stiffness of the fibre. This modulus is considered indicative of the integrity of disulfide bonds within the cortex, particularly in the wet state where weaker hydrogen and ionic bonds are disrupted (Breakspear *et al.*, 2024b). The cuticle has been shown to have negligible influence on the stress–strain curve (Robbins and Crawford, 1991) an observation that may lack immediate consumer relevance but is technically significant when isolating the effects of materials or treatments on the cortex alone. Nonetheless, at the macroscopic level, damage to the cuticle resulting from tensile extension, manifesting as cuticle cell lifting or delamination, has been documented too, and such changes are likely to impact the consumer’s perception of hair condition and manageability (Swift, 1999; Ruetsch and Weigmann, 1996). The torsional behaviour of hair has been found to reflect contributions from both the cuticle and the cortex, with each component providing a proportionate influence (Wolfram and Albrecht, 1985; Wortmann and Wortmann, 2014). Currently, there is a gap in understanding the relative contribution of the fibre’s tensile and torsional

properties to the consumer experience of cosmetic treatments applied to the whole head of hair.

More recently, fatigue testing has gained prominence as a method for assessing the mechanical durability of hair fibres under repeated low-level stress. Unlike traditional tensile testing, fatigue testing adopts a probabilistic framework, measuring the likelihood of fibre failure due to crack initiation and propagation after the application of numerous cycles of small stress. This technique has demonstrated good capacity to differentiate between the intact root end of the fibres and the structurally compromised tip regions, as well as between straight and textured hair types (Marsh, *et al.*, 2021; Ngoepe *et al.*, 2021). Fatigue testing has also proven effective in detecting the impact of cosmetic treatments and specific ingredients, for example those aimed at restoring protein cross-linking within the cortex or the CMC structure throughout the hair (Marsh, *et al.*, 2021; Lourenço *et al.*, 2024; Zhang, *et al.*, 2025). Overall, fatigue testing is intended to simulate mechanical stresses representative of daily grooming practices, such as brushing, tying or styling. However, with the exception of severely damaged hair, the statistical probability for fibres to fail in such tests typically spans tens of thousands of stress cycles. To date, it remains unclear which specific grooming or styling routines subject fibres to stress of sufficient magnitude or frequency to cumulatively approach these fatigue thresholds in real world consumer contexts.

Other analytical methods for hair fibre assessment

In addition to mechanical testing, structural variations and damage within hair fibres can be characterised through thermal analysis and a range of spectroscopic techniques. Thermal analysis is commonly used to complement tensile data, particularly in assessing the structural integrity of hair proteins. The thermal denaturation temperature reflects the level of KAPs cross-linking within the cortex, with lower values indicating loss of disulfide bonds, while the enthalpy of denaturation is considered to reflect the degree of organisation of both IFs and KAPs (Wortmann. *et al.*, 2002; Popescu and Gummer, 2016).

Spectroscopic methods provide molecular level insights into chemical alterations in the hair fibre. Fourier-transform infrared (FTIR) spectroscopy, for example, is widely employed to detect specific functional groups and bond disruptions, such as the presence of cysteic acid resulting from disulfide bond cleavage during bleaching or oxidative colouring, as well as lipid oxidation caused by UV exposure (McMullen and Zhang, 2020). These analytical approaches are particularly effective for evaluating the integrity of cortical proteins and overall fibre chemistry.

Conversely, investigations of cuticle structure and fibre surface morphology rely on advanced imaging techniques. Scanning electron microscopy (SEM) produces high-resolution images of the hair surface, which can be processed using image analysis software to quantify macrostructural damage, such as cuticle edge chipping, lifting or erosion (Gurden *et al.*, 2004; Tomes *et al.*, 2007; Lee *et al.*, 2016; Berg *et al.*, 2024). Atomic force microscopy (AFM) has contributed further by providing tribological data, including cuticle surface roughness, topography and nanomechanical properties such as hardness and friction (Poletti *et al.*, 2003; Bhushan and Chen, 2006).

Hair assembly testing

Together, the above methodologies have significantly advanced understanding of the structural and chemical consequences of cosmetic treatments on hair. However, as highlighted in the previous paragraphs, the extrapolation of single fibre data to the head-of-hair assembly behaviour remains scientifically tenuous. To improve relevance of technical fibre data, *ex vivo* laboratory testing using hair tresses is widely employed and assumed as providing consumer relevant measurements of the cosmetic treatment effects on hair. These experiments typically measure the macroscopic response of hair assemblies to the combination of mechanical forces, simulating some aspects of consumer handling of the hair or assess visible changes in hair bulk and surface attributes using two- or three-dimensional image analysis. Standard cleansing and conditioning routines are known to both remove and deposit ingredients, which in turn aim to soften the hair, enhance shine, reduce frizz and static and improve manageability, including combing (Robbins, 2012, pp.643-644). A variety of leave-on products are also formulated for application after washing or between washes, designed either to enhance these aesthetic effects or to support mechanical manipulation for styling purposes (Robbins, 2012, pp. 336-342). Notably, the greater the divergence between the desired hairstyle and the hair's natural three-dimensional form, both at fibre and assembly level, the more specific and effective the cosmetic intervention must be (Robbins, 2012, pp.643-644).

As a methodology, tress testing is also considered more adaptable to consumer experience in terms of product dosing, application method and controlled humidity conditions, thus also allowing for systematic investigations of the impact of these factors on product performance on a realistic hair mass. When combined with single fibre analysis, tress testing also supports some extrapolation of individual fibre data to full-head behaviour. Despite these advantages, current tress testing methodologies present some gaps. Interpretation of the fibre/product interactions is often over-reliant on theoretical models which may not capture the complexity of real-world hair behaviour.

Furthermore, curlier textures remain underrepresented in empirical work due to the lack of accepted methods for data capture and analysis.

The publications included in this PhD thesis address several of these gaps. In particular, the hair fibre interactions and resulting assembly properties are examined in the first two articles with the contribution of some human-derived or human-centred data. The curlier hair research gap is then addressed mostly from a consumer-centred perspective in both hair taxonomy articles, whilst maintaining the material science-based theoretical underpinning by referring to the hair manageability framework of Robbins and Scott (1978) and related fibre science.

The psychological and social significance of human hair

The most compelling scientific evidence for the personal and psychological importance of hair lies in the documented impact of hair loss. Disorders involving hair loss and their associated psychological burden are frequently reported in clinical research, typically measured through validated tools assessing mental health and wellbeing such as Quality of Life (QoL) index, the Beck Depression Inventory, and the Hospital Anxiety and Depression Scale (Schielein *et al.*, 2020; Kim, *et al.*, 2022; Muntyanu *et al.*, 2023). Beyond the clinical context, the social and cultural meanings of hair are widely explored through literature, film and visual art (Tarlo, 2016; Synnott, 1987). A prominent strand within both academic and artistic domains focuses on the influence of Eurocentric beauty standards and professional norms on women of African descent. A recurring theme across media and academic research is the internalisation of negative judgements and attitudes towards natural hair textures, often resulting in the early and regular use of chemical straightening treatments (Jarab, 1985; Weitz, 2001; Canella, 2020). In recent years, growing resistance to the historical and ongoing stigmatisation of textured hair has contributed to the emergence of online communities that promote the aesthetic value of natural hair styles. These spaces are often framed not only as beauty discourse but also as platforms promoting mental health and wellbeing via hair grooming as a form of selfcare (Mbilishaka, 2018; Ndichu and Upadhyaya, 2019; Goins, 2021).

Another evolving area of inquiry that concerns hair is ageing body image and the related adaptive hair strategies employed, mostly by women. Hence, individual motivations for hair colouring, styling and daily grooming practices have been found to be neither universal nor static over time, nor can they be understood solely through the lens of fashion (Ward and Holland, 2011; Williams *et al.*, 2020; Cecil *et al.*, 2021; Daniels *et al.*, 2025).

Amid the above fields of hair research focusing on its personal and social significance, the increasing global diversification in beauty norms including hair colour and texture will necessitate a more nuanced interdisciplinary theoretical and methodological approaches.

The publications within this PhD thesis collectively address this opportunity, as, to varied degrees, they draw on interdisciplinarity as a principle for hair testing development with the aim to inform cosmetic innovation for the purpose of wellbeing.

The construct of human beauty

The concept of human beauty has been shown to be culturally and socially constructed, with different standards applied across time and place. Accordingly, both human beauty and hair aesthetics are researched from multiple perspectives and disciplines. For example, positive appraisal of facial beauty has been linked to internalised preferences for feature symmetry and averageness wired in the brain from an early age and consistent across cultures, a position rooted in the principles of evolutionary psychology which argue that evolutionary pressure has placed a premium on visible signs of health and fertility (Fink *et al.*, 2006; Yarosh, 2019; Dimitrov and Kroumpouzos, 2023). However, these views have been critiqued from multiple perspectives. For example, neurological and cognitive research highlights that the brain is highly flexible and adaptive organ that responds to and learns from experience, thus the perceptions of beauty norms can be altered (Stotz, 2014; Axelrod *et al.*, 2023). Feminist scholars have further argued that evolutionary psychology theories with their emphasis on biological gender differences are reductionist and deterministic and can be misused to reinforce inequalities (Tiefer, 2004; Wolff, 2006; Forbs *et al.*, 2007). Other critiques acknowledge these tensions but call for a more nuanced approach that recognises the opportunities for mutual enhancement and integration of these disciplines for the purpose of better understanding of human behaviour, and for promoting equality and social change (Leisen, 2007; Buss and Schmitt, 2011; Kelly, 2014; O'Neill, 2015; Davies, 2021).

Beauty norms further intersect with power relations based on class and race thus resulting in hegemonic standards seen by many as oppressive (Capodilupo and Kim, 2014; Irvine, 2017; Sarpila *et al.*, 2020). As a result of these intertwined social and cultural influences and the growing complexity and availability of beautification products and services, recognition of beauty's centrality to personal identity and social worth is growing (Kuipers, 2022). More recently, the traditional visuality of beauty has been contested (Ruggerone and Stauss, 2020) and growing research on multisensory experiences in art, beauty and consumer behaviour highlights the need to transcend purely visual perspectives (Balaji *et al.*, 2011; Drobnick and Fisher, 2012; Freeland, 2012;

Spence and Gallace, 2011). Thus, touch and smell, which have already been researched in relation to cosmetics, have gained greater importance for aesthetics and wellbeing research.

Scalp hair has been somewhat less studied in such a manner but its proximity to the face and its relative malleability are frequently utilised by people to express identity and as a personal response to socially enforced aesthetic standards (Dadzie *et al.*, 2017, pp. 315-330). Moreover, hair-based discrimination based on texture and greyness has been reported too (Synnott, 1987; Patton, 2006; Daniels, *et al.*, 2025). These dynamics underscore how hair functions not only as an aesthetic feature, but also as a marker of and a means for negotiating and asserting personal identity and social belonging throughout life.

Furthermore, while the visual appearance of hair plays a central role in how it is perceived by others, the tactile experience constitutes a uniquely personal sensory experience. For instance, touch plays an implicit role in evaluating hair, as the texture of the hair assembly is crucial not only for visual qualities like shine or frizz but also in personal hair management practices (Boucsein *et al.*, 2002). Consequently, alongside product performance, research into the multidimensionality of hair aesthetics and grooming practices is needed.

A contribution towards closing this gap is made by several of the articles included in this PhD body of work by applying interdisciplinary research methodologies in an innovative manner. The work also foregrounds the existence of personal and emotional investment in hair grooming, and beautification more generally, that extends beyond aesthetic outcomes and is linked to selfcare, social recognition and wellbeing.

Interdisciplinarity: theory and practice

Cosmetic research has been described traditionally as a multidisciplinary field with main emphasis on the successful development and testing of ingredients and products, and involving chemistry, skin science, and pharmacy (Barel *et al.*, 2014, pp. 1–2). These scientific fields share an epistemological foundation rooted in objective data collection and analysis. When human-centred studies beyond dermatology have been conducted for the purpose of informing cosmetic research in the past, they would have been considered as sitting in the domains of sensory or marketing research.

To date, research focused on fibre- and tress-level material assessments has largely remained disconnected from the psychological and sociocultural explorations of hair, as these domains operate under fundamentally different epistemologies. Material science is grounded in objectivity, but the degree of experimental control often necessitated in

material testing may limit the consumer validity of findings. In contrast, social science research is centred on subjective human experience and is often context-dependent despite following established protocols to ensure analytic robustness and, where applicable, generalisability. To be able to draw fully on the richness of these epistemologically distinct fields, an interdisciplinary convergence is possible, however it should be shaped by critical methodological oversight directed by the overarching study aims.

The concept and practice of interdisciplinary research (IDR) can be broadly defined as an approach that integrates methods, data, and perspectives from multiple disciplines to advance understanding and address problems beyond the scope of a single field (Facilitating Interdisciplinary Research, 2005, p.2). In addition to the focus on solutions, IDR scholars have identified its potential for improved value to stakeholders such as the researchers and funders (Barry and Born, 2013, pp.1-56). Typical examples of IDR include fields such as human-computer interaction where human observational techniques such as ethnography are utilised for technological development. Although fast moving consumer goods like cosmetics have not traditionally required this level of interdisciplinary integration, this is beginning to change. Technological and social trends toward AI-facilitated health management and personalisation increasingly encompass cosmetic consumption, creating a need for more holistic, consumer-centred research of skin and haircare practices (Hung *et al.*, 2020; Flament *et al.*, 2021).

IDR presents inherent challenges for scholars, such as methodological tensions between disciplinary specialisations and determining the extent to which distinctive contributions of the constituent fields are preserved (Newell, 2001; Aboelela *et al.*, 2006; Boon and Van Baalen, 2018; Mazzocchi, 2019). Notwithstanding such tensions, the rationale for pursuing interdisciplinary inquiry within the cosmetic and social sciences is compelling, given the profound personal, cultural, and economic dimensions of the subject matter.

The body of research represented in this PhD thesis has addressed some of these challenges via stepwise methodological evolution, predominantly within the context of hair studies. The first two studies are more akin to multidisciplinary research, followed by the review article, and then the application of social science methodologies to hair grooming and styling. The final study seeks a more theoretical interdisciplinary integration, which is also innovative in bridging several subject fields.

Summary of published research included in this thesis

The following section summarises all publications that comprise this PhD thesis. Each publication is firstly introduced in the context of the knowledge base and research methodologies commonly employed at the time of publication. Furthermore, the introductions highlight the most significant contextual knowledge informing the holistic aim of this collective body of work. The methods are introduced at length as they illustrate the interdisciplinary approach and are critiqued both in the respective context of each study and generally. The main results and related discussion points are covered only to a degree that facilitates the critical evaluation of each study. The contribution of each study is analysed in the context of the specific field and its accepted methodology at the time of publication, as well as in relation to the development of the overall body of research that this thesis represents.

Article 1

New, S., **Daniels, G.** and Gummer, C.L., 2018. Measuring the frequency of consumer hair combing and magnitude of combing forces on individual hairs in a tress and the

implications for product evaluation and claims substantiation. *International Journal of Cosmetic Science*, 40(5), pp.461-466. <https://doi.org/10.1111/ics.12485>.

Context

Historically, hair combing has been regarded as an “acid test” for the evaluation of conditioning effects associated with cosmetic treatments (Robbins, 2012, p. 642). In 1978, Robbins and Reich advanced the field by introducing the first theoretical model of hair combing (Robbins and Reich, 1986; p.1). Their theoretically derived equation incorporated the following fibre level properties: kinetic and static friction, electrostatic charge, stiffness, fibre curvature and diameter. It provided a means of comparing the relative contributions of these parameters, in conjunction with cosmetic interventions, to the resistance encountered during combing, albeit the term used was combing ease. Within this model, it was proposed that, for straighter hair types, fibre friction, static charge, and stiffness constituted the primary properties subject to modification by conditioning formulations.

In parallel with these theoretical developments, that period saw the introduction of mechanised combing testing in which a comb was drawn through straight hair tresses under controlled velocity, while the resulting combing force, typically expressed in millinewtons, was recorded (Newman *et al.*, 1973; Gamez-Garcia, 2007). This force of resistance was hypothesised to arise from a combination of inter-fibre interactions: fibre alignment, compression between comb tines, fibre-to-fibre cohesion and the resolution of tangles. These investigations facilitated systematic exploration of the relationships between single fibre characteristics, hair assembly behaviour and the effects of conditioning interventions (Newman *et al.*, 1973; Kamath and Weigmann, 1986; Jachowicz and Heliouff, 1997; Gamez-Garcia, 2007).

The success of this early work established combing force (ease) measurement as a standardised methodology for the assessment of hair surface characteristics following cosmetic treatments, most notably in the wet state (Robbins, 2012, p. 649). Building upon these foundations, later studies utilised ATM to investigate the hair surface at nanometre resolution. These studies demonstrated the presence of conditioning material on the hair surface, and the resulting reduction of surface friction of damaged hair to the levels below that of virgin fibres (Bhushan and Chen, 2006; Wei and Bhushan, 2006)

Combing studies on straight hair have conventionally been performed on tresses of defined weight and length, under the implicit assumption that the recorded forces are distributed evenly among all fibres in a tress. This simplifying assumption facilitates the interpretation of assembly level testing and partially underpins the explanation of single

fibre mechanical data by the effects of cosmetic actives. An additional experimental paradigm linking single fibre and assembly level behaviour has been the enumeration of broken fibres within a tress following repeated, usually mechanised, combing cycles. Such studies have consistently reported a negative correlation between the use of conditioning products and breakage in straight hair (Robbins, 2006; Robbins and Kamath, 2007). Here again, the probability of breakage is assumed to be evenly distributed among fibres. However, the scalability of these “working” assumptions to the combing of a full head of hair, which typically comprises 80,000 to 100,000 fibres, is less straightforward. Consequently, the extrapolation of findings from single fibre and tress models to whole head performance is increasingly tenuous when considered against the complexities of everyday hair care.

Another methodological issue with single fibre and tress-based experiments is their contingency upon the appropriate hair sampling protocols, treatment standardisation, adequate replication and appropriate statistical analyses. *In vitro* testing of hair tresses, grounded in principles of material science, typically employs compounded hair from multiple donors, utilising 6–10 replicates per condition (Evans, 2010, p.225). The principle of using tresses standardised to a specific hair type improves the precision of the test results, but reduces the generalisability of the test, even within the defined hair type. Furthermore, the statistical significance obtained in such laboratory studies may not necessarily equate to consumer-perceived relevance. For this reason, these experimental strategies require continual critical evaluation and methodological refinement to enhance their applicability to consumer experience.

Aims

The present study was designed to examine the assumptions underlying fibre behaviour within a tress under wet and dry combing conditions, whilst representing distinct hair types and varying degrees of chemical damage associated with bleaching.

Materials and methods

Two hair types were tested, hair from Asian (Chinese) origin and Caucasian hair. Straight hair was specifically selected to ensure that curvature effect on combing is eliminated and in line with the prevalence of straight hair testing reported in scientific and technical industry literature at the time of the study. The selected two hair types have been reported to differ in hair diameter and cross-sectional area, as well as in hair surface topography, with average Asian hair fibre cross sectional area being larger and less elliptical than average Caucasian hair (Franbourg *et al.*, 2003). These characteristics of hair geometry are related to fibre’s increased torsional and bending moduli (Wolfram and Albrecht,

1985; Wortmann, *et al.*, 2014). The differences in cuticle scale structure, i.e. the number of scale layers and the degree of overlap in Asian hair are reported to be smaller, thus creating a smoother surface than in Caucasian hair (Wei and Bhushan, 2006). Based on these hair differentiators, it was hypothesised that the single fibre and, consequently, tress combing behaviour of Asian and Caucasian sourced hair would differ in dry and wet states. Additional conditions, in line with common industry practices, were introduced by bleaching the tresses and by treating them with a commercial hair conditioner.

The single fibre response to combing was tested by removing it from the tress, attaching it to a custom-made load cell and then reattaching it to the tress. Each tress was then subjected to 100 combing strokes (equal number on each side) with the tress being subjected to blow drying /or submersion in water for “re-tangling” after each 10 combing strokes (referred to as combing sets). Three tresses were tested for each condition. The load experienced by the load cell attached to the single hair fibre was measured and reported via software call TookKit. A load of 1g (9.81mN) was selected as threshold for the identification of a “load event”, provided that the force returned to approximate 0 value. Most fundamental combing articles report dry combing loads to be >10g, with wet combing loads being significantly higher, >50g, hence this threshold was deemed sufficiently low. The number of load events for each combing set, and the maximum and minimum loading reached within the events were reported. The aim was to quantify the probability of a hair fibre becoming involved in a load event. An additional dimension of the study was to contextualise this probability to the combing routines that are representative of the consumer’s behaviour. Combing frequency per day and number of combing strokes were considered of relevance and explored via an online survey. The manual combing speed in the experiment was also calibrated to the speed of combing of 10 female participants (5 Caucasian and 5 Asian) who combed their hair with a comb with a special mark, whilst being filmed. Using a video analysis software (Tracker, USA,) the speed of the comb was calculated to approximately 20cm/sec.

Results and discussion

The consumer surveys returned combined 231 responses from participants with Chinese and Caucasian hair, indicating an average of 1.6 combing occurrences per day, with a mean of 16 ± 2.3 strokes.

The main experimental data was described as “single fibre load event probability” meaning the % of hair combing strokes where loads of >1g were recorded. Dry hair combing returned very low probability (<20%) for a single fibre to become involved in a load event, irrespective of the hair type and status (bleached or non-bleached). This outcome has two main implications. Firstly, in the dry state, variations in single fibre

friction and stiffness due to fibre geometry and morphology do not cause significant variations in its propensity for interactions impacting on the tress combing behaviour. Secondly, combined with the estimates of daily combing strokes, the results suggest that dry straight hair is not likely to experience tensile-load related damage resulting from cuticle-to-comb direct contact or other forces arising from the comb movement.

The probability of load events diverged in the wet state with virgin wet Caucasian hair experiencing more loading events, albeit still remaining under 50%, whilst Asian wet hair results remained similar to dry hair. The behaviour of wet hair is generally explained with the adhesive forces of water, which, due to strong hydrogen bonding, create water films that hold fibres together (Fei *et al.*, 2017). Water induced swelling of the hair fibres, particularly of the cuticle cells, substantially increases surface roughness, thus generating inter-fibre friction. Combined, these effects suggest that, in the case of wet virgin hair, the adhesion forces between fibres lock most of the hair within clumps, thus preventing their contact with the comb and consequently the experience of load events.

Both hair types were equally impacted by bleaching. Whilst in dry state, the load event probabilities remained low; in the wet state they reached 100%, effectively generating more than one event in each set of 10 strokes. The application of hydrophobic rinse-off conditioner then reduced this probability for both types of bleached wet hair to that of the dry state. It can be hypothesised that, in the wet state, the swelling of cuticle cells in bleached hair generates a 3D structure of interlocking fibres different to that of unbleached hair, which increases the loading event probability. The addition of the conditioner lubricates most fibres' surfaces and reduces the probability of load events.

These experiments suggests that the probability of fibre damage and the possibility of breakage induced by combing is not universal for all fibres within the tress and appears to be of significant relevance only to unconditioned, wet, bleached hair.

When combined with the consumer combing behaviour data, these findings further highlight that combing dry hair may not be causing the damage to fibres implied in the interpretation of the conditioning test experimentation in the literature. However, in the specific context of very damaged hair, the combing ease in the wet state and hence hair protection effects of cosmetics are highly significant.

Methodology critique

The methodology of Article 1 is exploratory and comprises parallel laboratory experimentation and behavioural data collection. The respective findings were combined to interpret and reason the conclusion and recommendations related to future interpretations of combing and tensile hair testing. The strengths of the methodology

include the application of a sensitive load cell for measuring ranges from 1-100g (gram force), assessing the single fibre behaviour/interaction *in situ*, replicating realistic combing speed. A limitation of the test design is that it did not explore variables such as degrees of surface damage (e.g. lightly and strongly bleached hair) and degrees of conditioning effect, which could return a better differentiated reflection of the tensile forces experienced by single hair during combing. Another limitation of the study is the experimentation replicas for each condition being on the lower side of the typical number, which was reflected in the choice of descriptive statistics.

The parallel combing-habit survey was also of a small scale. It included participants of both hair types but, critically, their combing habits were not deemed statistically different, hence result interpretation did not differentiate hair types. Large sample sizes could improve accuracy of data, and specifically daily combing frequency.

Contribution

Firstly, this study contributes to the understanding and interpretation of established industry methods for combing and mechanical testing. It argues that, because single fibre loads exceeding 1 g during the combing of dry straight hair are unlikely, the relevance of dry fibre characterisation using tensile testing to consumer behaviour is limited. The findings also suggest that the common assumption of equal tensile load exposure in single fibre testing may overestimate the benefits of hair products, particularly with respect to breakage. Methodologically, the study highlights the value of incorporating human-centred data to complement materials science-based research, specifically to the critical interpretation of results.

As the first in a series of publications comprising this body of research, the study links, albeit through small-scale data, all three domains of hair research. It examines single fibre behaviour in relation to selected characteristics (e.g., straightness and morphological variation associated with different phenotypes, as well as oxidative damage) and extrapolates these findings in the context of the reported human combing behaviour. It also represents the first attempt to explore in more detail the hair combing experience model described by Robbins and Scott (1978). The choice of experiments reflects the historical prominence of combing, conditioning and related mechanical testing in the literature. However, other characteristics such as hair volume (or limpness) and fly-away tendencies, also discussed by Robbins and Scott (1978), are of relevance to consumers with straight hair too. Thus, the following hair volume and alignment study further addresses this gap.

Article 2

Daniels, G., Tamburic, S., Benini, S., Randall, J., Sanderson, T. and Savardi, M., 2021. Artificial Intelligence in hair research: A proof-of-concept study on evaluating hair assembly features. *International Journal of Cosmetic Science*, 43(4), pp.405-418. <https://doi.org/10.1111/ics.12706>.

Context

From the user's perspective, the desired visual qualities of a head of hair should be achievable through the application of appropriate products and styling techniques. From a formulation innovation standpoint, supporting the user in achieving these goals draws on all three domains of hair research: single fibre responses to treatments; the hair assembly qualities and the application of consumer relevant and measurable criteria for assessing these (Figure 1).

The theoretical framework for hair experience, a term applied to consumer experience of their head of hair, developed by Robbins and Scott (1978), identifies the following subjective visual hair properties: body limpness (understood as hair looking flat) and flyway (referring to single fibres separating from the bulk of hair). The authors also identified the following single fibre characteristics that can be used to predict the hair assembly appearance (Robbin and Scott, 1978):

- i) fibre diameter, curvature, stiffness, and static friction are inversely proportionate to limpness (e.g. finer, straight and softer fibres are associated with hair limpness);
- ii) static charge at the fibre surface, with smaller mitigating effects of the fibre curvature, stiffness, and weight, is positively correlated to the flyway.

The proposed associations are presented as predictions which could be used for cosmetic product design. It is notable that this framework is constructed around consumer "problems" and refers to cosmetic products in terms of their capacity to mitigate or resolve these. Other technical terms describing visually the hair assembly have emerged over time: hair body or volume (used interchangeably), usually defined as the space occupied by the hair, and frizz, understood as the degree of fibre misalignment within it and at its edges.

In practical terms, the generation of hair assembly volume requires an increase in the inter-fibre spacing, which consequently reduces fibre alignment. While this effect is partly dependent on the skill of the stylist in manipulating the hair, cosmetic treatments can also make a substantial contribution. In particular, increased hair fibre stiffness has been

shown to promote volume, as stiffer fibres exhibit a lower tendency to align closely with one another (Hough, *et al.*, 1976). Additionally, inter-fibre friction helps maintain the misaligned fibres cross-junction points, thereby preserving the increased spacing between them (Evans, 2018; Galliano *et al.*, 2021). Typical cosmetic ingredients that increase hair stiffness and increase fibre cross junction friction are some polymers (Martiny, 2002; Gillece *et al.*, 2022).

The first instrumental assessments of hair body were mechanical, based on measuring the force required to pass a tress through a ring of defined diameter, thus effectively applying a similar principle to combing, forcing fibres into smaller space and into higher level of alignment (Robbins and Crawford, 1984). These were superseded by tress image analysis, thus transforming the 3D nature of the assembly to 2D surface area values (Clark *et al.*, 1991; Robbins, 2012: pp. 686-689). Whilst the nature of the mathematical value extraction evolved over time from manual to software-based, the principle remained based on estimating as accurately as possible the total surface area of the hair tress on the image. This method also allowed for monitoring values over a set period and over humidity variations. Similarly to combing experimentation, this method assumes that the tress data is projectable to the head of hair, thus it is of a direct relevance to the consumer.

Assessment of hair fibre alignment or misalignment has historically been limited, largely due to constraints in the conventional image analysis techniques, which were capable of detecting variation only at the periphery of the hair silhouette. More recently, polarized light imaging has been employed as an indirect method for evaluating fibre alignment, providing an indication of the overall tress organisation. This characteristic is often described as frizz, a term that appears to capture more effectively the consumer perception of this assembly attribute (McMullen, 2012, pp. 295-332). An increase or decrease in volume may also be accompanied by a varying proportion of hair fibres deviating from the main body due to static electricity, a phenomenon referred to as flyaway.

Following the above theoretical considerations, a research gap in understanding the volume, alignment, and flyway associations was noted. One approach to addressing this gap is offered by the application of computer vision techniques, developed for the purpose of simulating human vision for image analysis. Much of the technique is underpinned by supervised machine learning (ML) using large training datasets in which input features (for example, data points extracted from standardised images) are paired with known, labelled outputs that represent the characteristics of interest in the investigation (Khoei and Kaabouch, 2023; Tufail *et al.*, 2023). The algorithm learns a

mapping function from inputs to outputs during training, and the resulting model is then applied to new, unseen data with the objective of predicting the correct labelled outputs (Khoei and Kaabouch, 2023). Various mathematical algorithms can be employed as supervised learning models, each with different strengths, depending on the structure of the dataset (e.g. image complexity and nature of extracted features) and the performance requirements (e.g., accuracy, computational efficiency). These approaches are widely applied in fields such as medical image analysis, geospatial land-use mapping, and facial recognition. Beyond the term ML, the overarching term Artificial Intelligence (AI) is used to describe the main goal of creating machines that mimic human thinking and decision making.

At the time of this project, the only publications on ML-based hair assessment were focused on evaluating hair growth in clinical practice (Chamberlain and Dawber, 2003; Wang *et al.*, 2018), and hair detection and style classification of the whole head of hair (Wang, *et al.*, 2014; Muhammad *et al.*, 2018). The aims of ML in these studies ranged from creating more accurate measurement methods used for diagnosing and laboratory experimentation, to matching human's ability to recognise hair length, colour, texture and styles. These techniques are commonly based on supervised learning. However, in the discussion of this project, the terms ML and AI will be used interchangeably since the research was considered exploratory and "proof of concept" and was aimed at testing feasibility rather than achieving a fully validated ML-based hair classification model.

Aims

This study aimed to explore the effect of products (shampoo and a conditioner) on fine straight hair tresses through a combination of AI-driven image analysis and human assessment.

Materials and methods

Fine, medium-brown, Caucasian hair was selected, so that its body/volume and neatness/alignment would be considered its core visual qualities. Hair tresses of 3g-weight and 10cm-length were used, with sixty hair tresses tested in their undamaged (virgin) state, and sixty other tresses of the same origin bleached in a control manner, thus representing a damaged state of the same hair. All tresses were then subjected to three consecutive washing-and-conditioning treatments, using a shampoo and the corresponding rinse-off conditioner with volumising claims (commercial products). Each tress was photographed untreated and after one and three treatments, from three angles (-45°, front and +45°) so that the 3D dimension of the tress volume is better captured.

75% of the images were used for algorithm training, and the remaining part for testing the classifying algorithms. The image analysis and algorithm training were based on four extracted image features: global hair volume, upper, mid, and lower hair volumes (following the sectioning of each tress into three, based on 1/3 of the length of a straight line connecting the top and the lowest detected point of the tress) and an alignment feature extracted following a published methodology. The output labels were based on the treatment time point that each image represented (t0 untreated, t1=after one treatment, t2= after three consecutive treatments).

The initial stage of the project produced a training dataset of images and the development of the feature extraction technique, which were shared in the public domain in a separate publication aimed at researchers in computer vision (Savardi *et al.*, 2020). The training dataset development included the identification of hair assembly qualities of relevance, considerations of extractable image features reflecting these qualities, and choices of appropriate treatments intended to alter these features. The dataset contained 1080 images split equally between two subsets: virgin and bleached hair. To date, the data set has recorded 635 views and 182 downloads.

To assess the consumer relevance of the strength of treatment effects, a visual tress test was conducted with 50 naïve assessors comparing the untreated and the three-times treated hair. The assessed hair parameters were tress volume, hair alignment, and hair flyaway. The first two dimensions corresponded to two of the training data set features: global hair volume and alignment, while the flyaway did not, as the ML-based hair detection process could not reliably recognise flyaway. However, it was included in the human assessment to ensure that the assessors clearly distinguished flyaway from volume, and because it is a consumer relevant quality of straight dry hair. An extension of the project included a visual assessment of the front images of a randomly selected group of ten tresses from each type conducted via an online survey, using naïve assessors (n=100). The assessors viewed image pairs representing all variations of the three time points for a given tress and were asked to identify which one has more volume, looks straighter, and has more flyaway. The tresses in these tests were not intended to represent trends in the data base, and were randomly selected, because the main aim was to explore the possibility of visual image assessment by humans. All three separate tests were conducted for virgin and bleached hair data subsets separately.

Results and discussion

Following the extraction of image features and various rounds of algorithm training and testing, two supervised classifying algorithms (Machine Vector Learning and Naïve Bias) were found to perform best against the following two criteria: a) accuracy in assigning

previously unseen images to the correct treatment time point; b) ability to correctly order two images of the same tress according to treatment sequence. Albeit different in the way they treat the data points used in the analysis, these two algorithms performed comparably, achieving over 90% accuracy when classifying unseen non-treated hair images versus the combined group of hair treated once and three times. When the treated hair was analysed as two distinct time points, classification accuracy dropped to approximately 70%. These findings applied to both virgin and bleached hair datasets. Consistent across both hair types were also the observed trends in global hair volume and alignment data points in response to the treatments. In each group, volume decreased with product application while alignment increased, an effect more akin to a typical conditioning treatment versus volumising effect.

Based on these findings, the naïve human panel compared t0 and t2 hair only and confirmed the AI-identified trend also returning a statistically significant decrease in volume and increase in fibre alignment in both virgin and bleached hair. The hair tress image assessment by humans and the AI extracted features of a randomly selected sample of images from the database returned mixed results suggesting that humans are not able to detect the features when presented with 2D images.

Key conclusion of this work is that, in straight hair, the volume and alignment are inversely related. Treatment effects thus involve a shifting balance between these two effects. Another interesting proposition arising from the AI analysis and classification is that the product effects are not cumulative, hence the lower accuracy in assigning hair between t1 and t2.

Methodology critique

This project was spurred by the growing trend for hair analysis and categorisation from images (Wang, 2014; Muhammad, 2018; Meishvili, 2024). This methodological approach is dependent on the quality of the image data, related to the light level and image focus, all of which have significant effect on the successful feature extraction. In this study, ambient light was used, and whilst the position of the camera was fixed, the process was manually executed, hence some deviations were assumed. This led to “noise” in the data; however, untreated and treated hair were clearly classified by AI.

As the feature extraction was based on pixel data and on the standard deviation of the histogram of oriented gradients, the ML mostly reflected the hair’s bulk quality and was not sensitive to the boundary quality e.g. flyway. Thus, the classification was not fully reflective of the human hair experience of straight hair quality dimensions. Consequently, the human data could not be used for algorithm validation, but they provided an

exploratory comparison aligned broadly with typical hair sensory assessment. To improve the familiarity of the naïve hair assessors with the features and thus the accuracy and sensitivity of the tests, the definitions of hair volume, alignment, and flyway were provided. However, this briefing did not constitute training, meaning that, from a sensory assessment viewpoint, the data accuracy could be further improved. Another approach in the future could be to combine ML and human assessment into one training data set.

Contribution

The main contribution of this article is in demonstrating the use of AI-driven hair image assessment as a feasible experimental design approach. Based on a relatively small training dataset and using publicly available image analysis techniques, this “low-tech” experimental data gathering could be advantageous for initial lab-based prototype assessments, providing that appropriate techniques for feature detection and extraction are applied and relevant thresholds for AI algorithms success are set. As the training data set and the accompanying codes were made freely available via an open access publication (Savardi *et al.*, 2020), this work contrasts with proprietary AI-related commercial research, which does not share the training datasets. This research and the accompanying dataset open the space for hair analysis that sits between the studies of the whole head of hair focused on style detection, and diagnostic data analysis based on microscopic images of the scalp and hair.

Another conceptual contribution of this work to the cosmetic field is in illustrating how AI-based analysis can be used for the exploration of data that was not statistically comparable, since the analysis did not make assumptions about the data quality and distribution. Traditionally, hair fibre and assembly data has been extensively scrutinised for variability. Despite that, a set of results within a given study could be prone to both types I and II statistical errors. To compensate for this, effect size is commonly manipulated, for example by mostly testing bleached hair which responds better to certain types of conditioning products, or by exaggerating product application doses. This article presents a new research paradigm based on exploring patterns in noisy data that is more akin to the variability of product effects in real-life scenarios.

Finally, the project also represents an expansion of personal research focus from the hair combing interactions towards multi-dimensional visual hair assessment, whilst maintaining virgins and bleached hair as major condition variables. Hair curl level was not introduced as a variable, because of the range of challenges in obtaining hair as well as the lack of prior research to support such complex research design. Still, these studies formed a foundation for shifting the research focus towards wider variety of hair types.

Article 3

Daniels, G., Fraser, A. and Westgate, G.E., 2023. How different is human hair? A critical appraisal of the reported differences in global hair fibre characteristics and properties towards defining a more relevant framework for hair type classification. *International Journal of Cosmetic Science*, 45(1), pp. 50-61. <https://doi.org/10.1111/ics.12819>

Context

Research on human hair diversity has been conducted for over a century. Early investigations typically classified hair into three broad phenotypic categories: Caucasian, African, and Asian (Trotter, 1939; Hrdy, 1973). This typological framework, originating in anthropological studies aimed at elucidating ancestry and cultural affiliations, has continued to inform subsequent work in both materials science and cosmetic research related to hair. More recently, advancements in microscopic and spectroscopic techniques have facilitated detailed characterisation of hair's geometric and surface morphology patterns, along with their variability and global patterns of distribution, thus raising the question whether the three phenotypes are helpful for describing hair diversity (Loussouarn, 2016; Koch *et al.*, 2019; Lasisi *et al.*, 2021; Gaines *et al.*, 2023; Richena *et al.*, 2025). Another strand of research into these broad phenotype differentiations was focused on the chemical composition and microstructure of hair (Franbourg *et al.*, 2003; Liu *et al.*, 2004). In relation to cosmetics, further explorations of hair responses to environmental and chemical stressors such as high humidity, solar radiation, as well as bleaching, have generated knowledge of hair differentiation (Wortmann *et al.*, 2002; Franbourg *et al.*, 2003; Marsh *et al.*, 2021; Wortmann *et al.*, 2023, Breakspear *et al.*, 2024). This combined body of research has expanded significantly the knowledge within the first two hair domains (Figure 1). However, not all testing methodologies are equally universally applied; for example, testing straighter hair types significantly outnumbers studies of curlier and textured hair.

While gaps in knowledge remain, some studies have purposefully explored differences in human hair (Bhushan, 2008; Koch *et al.*, 2019), making a review article summarising all key findings timely and useful. Such a review can guide future research and specifically support studying curlier and more textured hair.

Review articles typically follow a structured process of data collection, evaluation and synthesis, although their methodologies and underlying assumptions can vary considerably. Selecting the most appropriate review method is therefore critical to ensure that the article's objectives are achieved. Considered amongst the most rigorous, systematic reviews are commonly employed in medicine and healthcare. They are

specifically designed to evaluate the effects of interventions by aggregating and comparing data from multiple studies often conducted on smaller cohorts, and answering a clearly defined research question, with particular emphasis on reporting the search strategy and a rigorous approach to data extraction and synthesis (Smith *et al.*, 2011).

However, systematic reviews are rarely undertaken within the field of materials science due to the variability in experimental protocols. As an alternative, semi-systematic reviews serve to provide historical overviews, map existing knowledge in cross-disciplinary fields, and establish a broad conceptual understanding of complex topics (Snyder, 2019, p. 335).

Since hair fibre science relies on a diverse range of testing methods, and because the tested hair samples are not standardised across studies, data from different studies is inherently heterogeneous. A semi-systematic review design was therefore considered more appropriate, as it provides a more flexible and adaptive framework for the data collection and analysis.

In addition, Article 3 employed a critical evaluative approach. Critical reviews aim to assess both the breadth of the research landscape and the consistency of findings across disciplinary boundaries (Grant *et al.*, 2009). Incorporating explicit critical analysis also aligned better with the review's aim while also reducing the subjectivity commonly associated with purely narrative reviews.

Aims

This review article had the overarching aim to gather up-to-date knowledge on hair fibre variability and appraise it for the purpose of identifying gaps and considerations for future hair type reporting and classifications.

Method

Preliminary searches identified that hair fibre research fitted broadly under three different combinations of search terms. Hence, a separate search strategy was developed and tailored to each of the three research subtopics: *Hair chemistry*; *Hair morphology, structure, follicle*; *Technical hair fibre properties*. Where articles reported experimental data across more than one subtopic, these were referred to separately as many times as appropriate. The main databases searched were ScienceDirect, known for publishing research in physical, engineering, analytical and materials sciences and PubMed/Medline, known for publishing life sciences and medical research, including human hair studies. Additionally, the Wiley Online Library and KOSMET databases were searched to identify relevant studies not indexed in ScienceDirect or PubMed. Within each database, multi-term searches were conducted using the advanced search options.

The reference lists of the selected publications were also reviewed for relevant articles, a technique also referred to as backward snowballing (Maki *et al.*, 2022). The main inclusion criterion for the studies was that at least two hair types, defined by curl level, geo-racial origin and/or colour, had to be included in the article. The exclusion criteria were: i) studies exclusively investigating one specific hair type's interactions with a cosmetic active ingredient and ii) studies that failed to clearly report the nature of the hair samples used. Given that research on human hair is not an extensively explored area, these criteria were considered appropriate for comprehensive data gathering whilst ensuring the robustness of the reviewed studies data.

Results and discussion

The first section provided a historical perspective on the scientific approaches to hair classification and specifically on the shifting emphasis from geo-racial origin (three phenotypes) to geometric hair feature differentiation. It was argued that the traditional classification into Caucasian, African, and Asian hair types, still commonly used in research articles, oversimplifies the vast diversity in hair and fails to account for growing intergroup variation due to mixed ancestry. The limited practical application of a classification system based solely on manual measurements of hair curl level was discussed too, highlighting more recent studies employing image capture and analysis of a large number of individual hair fibres for achieving more precise curl assessment (Lasisi *et al.*, 2021). The section concluded by emphasising the need for standardised reporting of hair characteristics in research communications to enable reliable comparisons across studies.

The second section offered a comprehensive review of the different physical characteristics of human hair by examining hair geometry and morphology. Substantial intra group variability reported in studies was highlighted as well, demonstrating again the limitations of the traditional phenotype grouping in capturing the complexity of human hair (Loussouarn *et al.*, 2016). Whilst highlighting the human hair diversity, these findings also strengthened the case for a more refined and inclusive classification framework.

The remaining sections reviewed the biochemical composition and microstructure of hair. It was highlighted that earlier research reported minimal differences in amino acid profiles across racial groups; however, more recent proteomic studies have identified subtle variations in keratin-associated proteins (KAPs) which may provide helpful approaches to hair differentiation at a micro level, rather than global hair classification (Dekio *et al.*, 1989; Laatsch *et al.*, 2014). Hair pigmentation was also discussed as a critical characteristic, shaped by the type, concentration, and distribution of melanin granules. Variations in the pigment granules were noted to contribute not only to hair colour, but

also to influence the hair responses to UV radiation (Liu *et al.*, 2004; Ito and Wakamatsu, 2011).

A range of fibre properties were reviewed in relation to the identified geometric and structural variability. Hair with the most circular and large surface area and more layered cuticle was noted for its high mechanical resilience, surface hardness, and resistance to humidity changes. In contrast, highly elliptical hair and thinner cuticle, showed higher fragility (Seshadri *et al.*, 2008; Oliver *et al.*, 2020; Ngoepe *et al.*, 2021). This section also highlighted that such findings were not explained in depth in many studies.

The final section of the article integrated all findings into a coherent understanding of hair diversity, reflecting accumulated knowledge to date. The main methodological challenges in hair research were outlined, specifically the need for more robust and transparent hair sampling, with several characteristics such as hair curl type, estimated cross-sectional diameter and colour, being suggested as critical common descriptors which would facilitate data comparisons and synthesis across studies.

Methodology critique

In keeping with the selected semi-systematic search methodology, the different parallel search techniques were designed to be more flexible, thus ensuring that all relevant articles are identified but may have still resulted in some publications being missed. Despite that, the full transparency of the search strategy and terms aids reproducibility and represents a methodological strength. Furthermore, to facilitate data analysis and synthesis, different datapoints from each study were reported under the pre-defined subtopic headings in one table, which improved the comprehensive structure of the analysis. The criticality was applied throughout and conducted through the prism of appraising the degree of hair differentiation and its contribution to alternative hair classification approaches. Thus, the adopted hybrid review methodology offered a customised approach needed to address the topic in a robust manner whilst maintaining flexibility in order to address all relevant sub areas and appraise the knowledge from multiple perspectives.

Contribution

The contribution of this article to the hair research community, thus, lies in its comprehensive synthesis and critical evaluation of the available knowledge within the multi-faceted field of hair fibre science at the time. Further value is added by the article's theoretical argument for conceptualising hair diversity as a continuum, which aligns more appropriately with increasing global variability in hair curl patterns. This conclusion is

supported by a more recent publication, analysing historic hair samples in the USA collected by anthropologist Mildred Trotter in the 1920s, which concluded that although hair traits are not entirely separable from ancestry, they exhibit continuous variation (Koch *et al.*, 2024). At the time of publication and to date, this review remains the only of its kind, based on the methodological approach as well as the cosmetic research orientation of the conclusions and recommendations.

Within this body of work, the review provided a theoretical consolidation of the author's materials science perspective on hair fibre variability. While situated in the first domain of hair research, it also established a foundation for extending investigations into the second and third domains, with particular attention to the under-researched characteristics of curlier hair types. The review further contributed to shaping the methodological and epistemological foundations of the author's ensuing research practice. It led to higher appreciation of the multidisciplinary nature of hair science and highlighted both the distinct and complementary roles of different analytical techniques and review methodologies. Taken together, these insights suggested that interdisciplinary approaches could provide a promising avenue for advancing fundamental knowledge in hair research.

Articles 4 and 5

Daniels, G. and Heitmayer, M. (2024). Towards a taxonomy for assessing and classifying the needs of curly hair: A mixed method, ethnographic and quantitative data study. *International Journal of Cosmetic Science*, 46(5), pp.746-760. <https://doi.org/10.1111/ics.12952>.

Daniels, G. and Heitmayer, M. (2024). Taxonomy for the assessment of the subjective experience of curly hair manageability. *International Journal of Cosmetic Science*, 46(6), pp.1074-1087. <https://doi.org/10.1111/ics.13008>.

Context

These two articles collectively address the complex challenges associated with the manageability of curly hair, integrating user perspectives with a technically informed analytical approach. As they represent two iterative phases of the same research project, they are summarised and critiqued together.

The micro- and macro-structural characteristics of curly hair fibres have been already comprehensively described in the preceding review article. However, relatively few studies have examined the ways in which curly single fibres interact with each other, and how their properties and interactions potentially determine the behaviour of the hair assembly. The theoretically derived equation proposed by Robbins and Scott (1978) identifies fibre curl level as a defining contributor to the hair assembly's body, combability, manageability, and style retention. These authors identified manageability as the easiness of achieving a style, however in the current body of work, the term is used more broadly. While the theoretical equation remains broadly relevant, higher standards of style retention and manageability are achievable today due to new generations of efficacious cosmetic materials and styling devices. Furthermore, the hair experiences identified by Robbins and Scott are of relevance mostly to straight and wavy hair. With the increased emphasis on curly and textured hair focused innovation, there is an opportunity to refine this model. Such refinement requires that new experimental variables are identified, and testing methods are adopted or developed to reflect the specific characteristics of curlier hair types.

So far, research on fibre-assembly associations has focused on the influence of fibre geometry and diameter on perceived hair assembly roughness (Wortmann and Schwan-Jonczyk, 2006; Galliano *et al.*, 2021) The latter study is of particular significance because it includes both straight and wavy hair (but not curly hair), thereby attempting to account for the effects of fibre curvature, while also considering the role of fibre misalignment in tactile perceptions. Fibre misalignment is also linked to visual hair characteristics such

as frizz, a feature of high relevance to curly hair. Hair management strategies to achieve frizz-free hair are subject of ongoing investigation, with research so far mainly focused on reducing the absorption of environmental humidity into the fibre (Martiny, 2002; Tanamachi, 2011; Uto *et al.*, 2024).

There is also recognition amongst experts that many established testing methods, and the interpretations derived from them, do not correspond to the language and experiences of consumers (Evans, 2013b). Building on the methodological and epistemological insights gained from the hair tress testing and review articles, the next research step was to develop a conceptual framework that integrates interdisciplinary perspectives into the study of curlier hair types. Such framework would support the technical methodology developments to address more directly the needs and management of curly hair.

In the social psychology, education, healthcare, and other behaviour-centred disciplines, mixed methods research design has been developed over time, combining qualitative and quantitative data to capture the complexity of human experience (Cameron, 2009; Alavi *et al.*, 2018). Several models are recognised, including sequential versus parallel, exploratory versus explanatory, embedded and convergent designs (Creswell *et al.*, 2008, pp.209-240; Doyle *et al.*, 2009). They are distinguished by the way the qualitative and quantitative data collection elements are conducted in relation to each other, in terms of sequence and purpose. However, scholars have cautioned against a too rigidly applied procedural approach, arguing that the strength of mixed methods lies in adapting designs reflexively to suit the research context (Timans *et al.*, 2019).

Qualitative data capture is of specific significance when approaching a new phenomenon, including in the context of mixed methods studies. Key considerations in qualitative research are how to account for the potential impact of the researcher's positionality when interacting with the participants, and the capacity of the participants to recall and describe their perceptions and experience (Coleman, 2019). Thus, where authentic behavioural data is required, ethnographic techniques could be more suitable, as the data capture is situated in the environment where these behaviours take place. Subjective Evidence-Based Ethnography (SEBE) is an example of such a method, developed for explorative purposes, which takes place over two stages. Firstly, the participant(s) video record themselves during the activity, experience or interactions which are of interest *in situ*, thus creating a First-Person Perspective (FPP) data file. This recording is then viewed together with the interviewer(s), known as Replay Interviews (RIW), thus prompting a conversation based on the observed behaviours, rather than on a prescribed interview schedule. The transcript of the recording of RIW is then analysed.

SEBE is said to reduce bias since it is based on observations (evidence), whilst allowing the participants to explain their subjective experience via their own language and context (Lahlou, 2014). A widely used method for qualitative data analysis is the thematic analysis framework described firstly by Braun and Clark (2008). The method includes the following steps: familiarisation with data, coding data, identifying themes, reviewing and finalising themes. The analysis may be semantic, based exclusively on the observed phenomena or latent seeking a deeper exploration of underlining dynamics.

A specific application of sequential, exploratory mixed-methods design is to develop a method for measuring the strength of different dimensions of the phenomenon of interest (Creswell, 2004; Creswell, *et al.*, 2007). The outcomes may range from a framework which conceptually outlines factors and their relationships, to taxonomy offering a systematic classification of factors including elements of hierarchy within and/or between them, or an instrument which allows for collection and processing of quantitative data. This gradation of outcomes, in combination with the adaptability of the mix methods design, offers the opportunity to develop research tailored to addressing the needs of curly hair. Such research fits in the hair manageability domains of research, as it is focused on human experience and behaviour, but aimed at informing single fibre and assembly research.

Aim

The combined aim of these two studies was to develop a taxonomy for assessing curly hair manageability needs with a focus on the consumer.

Methods

To achieve the stated aim, the studies employed an iterative, exploratory mixed-methods design, integrating qualitative data on hair grooming and styling experiences and behaviours in domestic settings with measurable data on hair characteristics, management practices, and perceptions. The research progressed through two cycles, as presented in a diagram from the original article, each using the above sequential design: a qualitative data analysis phase followed by a survey-based quantitative phase (Daniels and Heitmyer, 2024, p.1078).

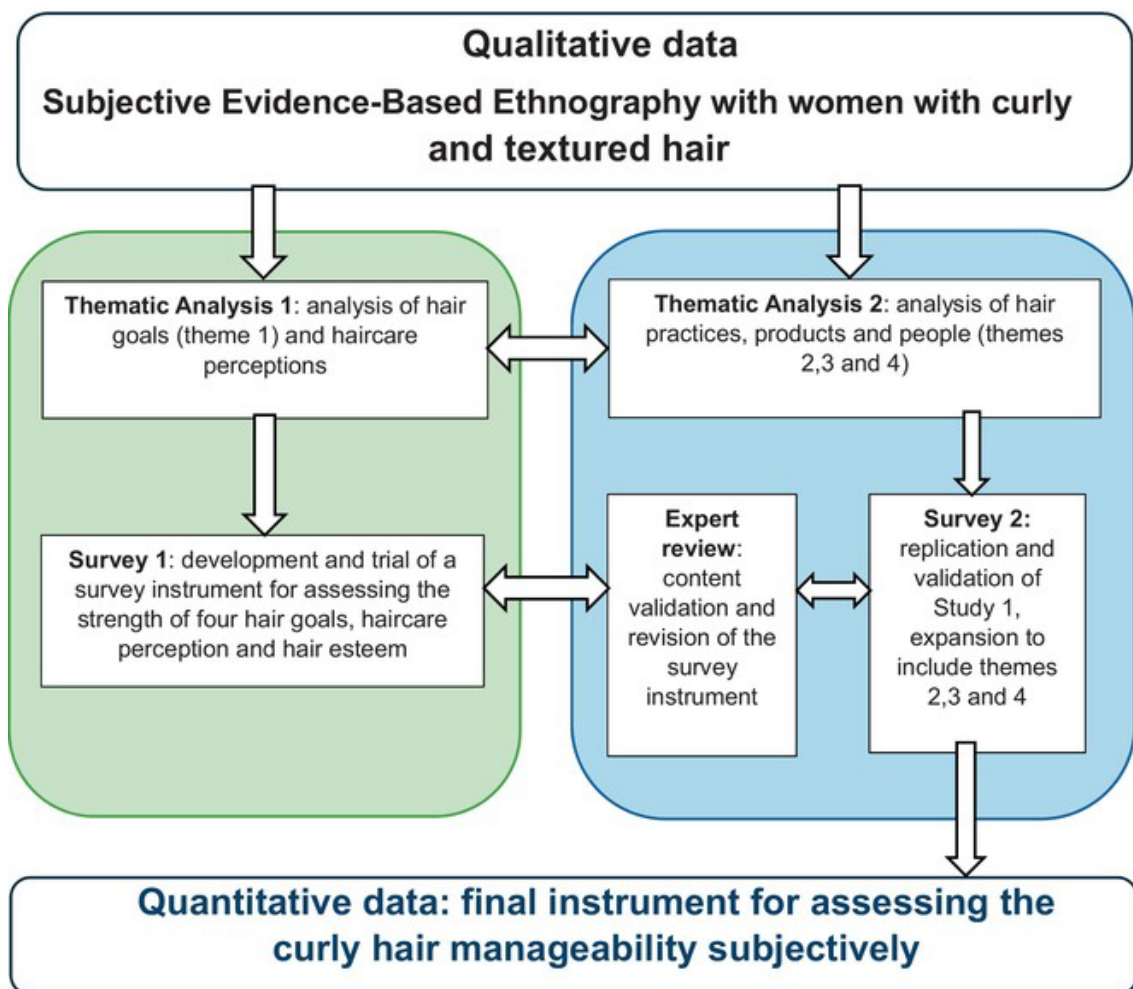


Figure 2. A flow diagram of the combined two-stage mixed method study design. Stage 1 is fitted within the green field (left) and stage 2 is fitted within the blue field (right).

SEBE was applied first with participants being instructed to record a typical grooming behaviour at home, followed by a video review meeting with the researchers, conducted face-to-face, where the researchers and participant discussed the footage. Following initial thematic analysis, the SEBE data was split, one major theme was further analysed and a survey generated. In the survey, groups of questions represented major subthemes, thus generating composite scores for each subtheme's level of importance. The survey also included demographic and hair characteristic related questions, haircare and styling perception-related questions, as well as a short "hair esteem" group of questions, which were an adaptation of a body esteem survey already used by other researchers for hair (Rosenburg, 1965; Bankhead and Johnson, 2014). Article 4 was published following descriptive and exploratory statistical analysis of various correlations.

In the second cycle, the remaining qualitative SEBE data was analysed, and its subthemes were integrated into an expanded version of the original survey. Seven

experts from diverse hair-related professional fields (cosmetic science, trichology, hairdressing education, and product development) also reviewed the survey questions and gave feedback and suggestions. The new survey data was analysed for scale validity and correlations. The questions and scale of the final survey were then published.

Results

Fourteen participants who self-identified as having curly or textured hair, Types 3 and 4 (Gittens, 2014: p.25) took part. The hair styling self-recordings ranged in length from 2 min 35 s to 47 min 18 s, whilst the interview recordings lasted 37 min on average, ranging from 26 to 51 min. These variations illustrate how diverse hair practices are and the free-flowing nature of the interviews. The four major themes emerging from the RIWs were: *perceptions and hair goals, products and tools, processes and practices, people and places of influence.*

The first major theme was further analysed, and the following subthemes (goals with subgoals) were developed.

- Aesthetic: reducing frizz, enhancing curl definition, achieving sleekness.
- Haptic: smoothness, softness and detangling.
- Practical: time efficiency, ease of maintenance and style longevity.
- Emotive: health, naturalness, and social recognition.

The first survey data comprised 212 valid responses. Firstly, the internal validity of each goal-related group of questions was tested. Aesthetic and haptic goals achieved good internal validity (Cronbach alpha>70) suggesting that individual questions, and as a group, represented consistently the measure of the respective goal. Some heterogeneity in the practical and emotive goal groups of questions was observed (Cronbach alpha<70). In the event of such inconsistency, the questions could be reviewed and expanded before repeating the test on new participant groups.

Various correlations between hair goals, characteristics, and perceptions emerged. The aesthetic goals were positively correlated with the other goals, as well as with hair esteem, meaning the stronger the aesthetic hair goals of the person are, the stronger all other goals, as well as their hair esteem, will be. Perceiving haircare as a form of selfcare was positively correlated with emotive goals and higher esteem, whilst perceiving it as chore was correlated with practical goals and negatively correlated with emotive goals and hair esteem. Whilst this result does not warrant categorising people as selfcare or chore orientated, it does make it clear that curly hair management carries a subjective emotional and practical burden.

At the second stage of the project, the processes and practices emerged to be based on an interdependency of the frequency and the length of time between washes. Common practices were reported: washed hair was mostly airdried, styling was mostly done with fingers and preceded by hair wetting on the occasions when the hair is not freshly washed. Processes were put in place to stretch time between washing and to utilise various leave-on product applications in this period. The product performance preferences were overwhelmingly for longevity of effect and time saving.

The second survey delivered 506 valid responses. It tested further the internal consistency of the hair goal construct with marked improvements in aesthetic goal (Cronbach alpha=73), retained the validity of the haptic and emotive goals, whilst the practical goals remained below the acceptable threshold of 70 for survey samples of >100 (Cronbach alpha=65) (Tavakol and Dennick, 2011). Thus, the practical goal group of questions emerged as the most difficult to develop, most likely due to variations in personal preferences and circumstances. Overall, the second article re-affirmed the taxonomy approach of systematising relevant hair-related personal and behavioural data in support of developing laboratory-based assessment of curlier hair types.

Methodology critique

These articles represent an adaptation of mixed methods research design, as two iterative cycles of a sequential mixed methods investigation, thus drawing on its inherent methodological flexibility. Due to the lack of prior published data on the topic, this flexibility was needed in order to respond to and utilise the gathered data most effectively. Specifically, the two cycles were planned with a view that the first one would be a pilot; however, the SEBE returned high volume and high-quality data that was deemed sufficient and generalisable, therefore rendering a second qualitative data collection unnecessary. Considering a set of qualitative data generalisable, is partly contingent on the participant numbers and the composition of the sample size as well as the nature of the data acquisition process. These are, in turn, related to the concept of data saturation, meaning that no new themes and/or codes emerge after a certain point of the analysis. It has been reported that an approximate range of 10-20 participants or multiples of 12 participants are the most common sample sizes for in-depth interview-based studies (Sampson *et al.*, 2013). Braun and Clarke, the authors of the thematic analysis framework applied to the qualitative data included in this body of work, have recently proposed an alternative approach to the data-saturation based sampling. In a critical review of published thematic analysis-based research, these authors propose that the construction of themes is a more flexible and evolving process, and that the sample adequacy decisions are based on how sufficiently meaningful the data is in the context

of the study's aim, also referred to as the information power of the sample (Braun and Clarke, 2021). Thus, the information power is determined by the quality, degree of specificity, and relevance of the data as interrogated by the researchers. In the hair-focused studies, the researchers estimated that a thematic saturation point was reached by the 12 participants, but two more interviews were organised to gain an equal hair curl type representation. This decision aligns with the information-power-led flexibility in deciding on the panel size, albeit representing a purposeful addition of participants. From a methodological perspective, this number was also considered sufficient for SEBE due to the richness of data provided by the nature of the FPP recordings (Lahlou, 2014). The results were analysed by two researchers, reflecting on the process on an ongoing basis. The themes and subthemes were considered in the context of significance to the aim, not just on the number of recurrences, but also drawing to a degree on the author's expertise in hair science. However, the second researcher was from a social psychology background and not familiar with the subject, thus mitigating the possibility of bias. This process could be viewed as an illustration of the strength of interdisciplinary research and teams.

The two surveys utilised different participants. The first cohort was smaller as was considered a pilot, whilst the second one was significantly larger. One consideration is that the curliest, also referred to as textured, hair was under-represented in the second sample, and this imbalance may have influenced the resulting survey outcomes. However, several validation steps were undertaken to ensure that the taxonomy framework is translated into a reliable instrument for measuring curly hair manageability needs and behaviours, e.g. checking internal statistical validity via the Cronbach alpha, improving external validity via expanding the survey sample, ensuring content validity by asking experts to review all questions.

Contribution

Collectively, these studies make an innovative methodological contribution to the field of hair research by combining cosmetic science with social psychology. Through mixed methods research, they deliver a structured taxonomy of curly hair needs, goals and practices. The term "taxonomy" captures well the context of this project, since it signifies classifying based on hierarchical structure by identifying large groups and their subgroups (Bailey, 1994). By incorporating SEBE, the research highlights the value of deeply personal consumer insights in product design and testing. This work, thus, lays the foundation for future interdisciplinary research on curly hair and for the development of more effective hair care products.

The project also supported further applications of qualitative research for the purpose of assessing the impact of cosmetics in the context of multi-sensory aesthetics experiences and their social significance.

Article 6

Daniels, G. and Khadaroo, A., 2024. Blind and partially sighted women's make-up: A narrative of practice, perseverance and empowerment. *Critical Studies in Fashion & Beauty*, 15(2), pp.201-220. https://doi.org/10.1386/csfb_00078_1.

Context

Academic literature on the construct of human beauty is extensive. Although beauty is considered to be a culturally defined phenomenon, some cross-cultural and enduring facial characteristics such as facial feature symmetry, closeness to average female or male facial traits and skin complexion have been reported as being perceived as markers of attractiveness (Fink *et al.*, 2006; Little *et al.*, 2011; Chen *et al.*, 2014; Haegele and Hodge, 2016; Hong *et al.*, 2017). Cosmetics, including makeup, are typically used to "correct," conceal, or modify facial features to align them with prevailing standards of beauty or to signal social belonging. Consequently, for many individuals, beauty and makeup use are experienced primarily through a visual dimension. However, other sensory modalities also contribute to aesthetic experiences of cosmetics; for example, research in cognitive and affective psychology has shown that the scent of cosmetic products can influence the overall beautifying experience and its perceived effects (Pense-Lheritier, 2015; Spence and Zhang, 2024).

More recently, the visual dominance of fashion and beauty aesthetics has been critiqued as a mechanism that reinforces normative biases, perpetuates stereotypes, and sustains ableist ideals (Kaiser and Green, 2021). The ubiquitous use of social media is reported to magnify these issues (Fardouly *et al.*, 2015; De Valle *et al.*, 2021; Bonfanti *et al.*, 2025); however, some scholars have also identified its potential to promote body positivity and health-oriented approaches to appearance (Raggatt *et al.*, 2018; Kleisner *et al.*, 2023).

In this context, individuals with visible physical or sensory disabilities may be less inclined to pursue social media exposure or engage with content driven primarily by visual aesthetics. Nonetheless, they still require meaningful opportunities to develop and evolve their sense of body image and personal identity. The representation of disability on social media, including content created by disabled people themselves, is highly diverse. Ranging from portrayals of "superhuman" achievements, often linked to elite sporting events, to awareness-raising videos, varied strategies are being employed by an increasing number of disabled influencers to build interest and trust (Columna *et al.*, 2013; Kearney *et al.*, 2019; Södergren and Vallström, 2022). On this backdrop, blind and partially sighted (BPS) people's engagement with fashion, cosmetics, and their social media representation has been researched only very sporadically. However, it has been

reported that they might wish to look like sighted people in terms of clothing and styling, rather than draw attention by presenting differences in their appearances (Kaplan-Myrth, 2000; Li *et al.*, 2022). Furthermore, cosmetic usage to modify appearance in accordance with social context (i.e. a work meeting or going out) is of interest to some of them, too (Pradhan and Daniels, 2021). This very limited research on disability representation, combined with the research on the human construct of beauty and social media, point to a gap in understanding how these domains intersect. Moreover, the concept of social disability, which emerged as a critique to the traditional view of disability as a medical condition, argues that modern society should focus on removing the barriers that disabled people face when participating in daily activities due to outdated cultural and environmental social constraints (Barnes, 2012, pp.12-29). The concept of social disability is, thus, relevant to the human aesthetic experience as discussed already, but also related to accessibility challenges that disabled individuals encounter as consumers.

In recent years, the cosmetic industry has attempted to address issues of representation and accessibility with applications such as voice-enabled makeup assistant (Ester Lauder, nd), products with adapted design (Kohl Kreatives, nd) and product application devices (L'Oreal, nd). However, at a more basic level, universal product design is considered as potentially more effective for meeting the needs of a wider group of consumers as possible, including consumers with disabilities (Aslaksen *et al.*, 1997).

Innovation is considered best spurred by research in human perceptions and behaviours, before working on prototypes and their assessment. User design research is particularly developed in technology development, including assistive technology (Mallin and Carvalho, 2015; Santos *et al.*, 2019; Ortiz-Escobar *et al.*, 2023). With the growth of social media, it has become increasingly possible to access and analyse publicly available attitudinal and behavioural data, such as blogs, vlogs, and other testimonials, before elucidating further information directly from participants. The advantages of qualitative research using social media content, compared with traditional interviews, include its capacity to capture a larger and more diverse range of individuals, to access specific groups, and to generate data that are less susceptible to researcher influence. In some contexts, social media-based data collection is also less intrusive and can therefore produce richer insights than interviews conducted outside a participant's natural environment (Andreotta *et al.*, 2019). However, social media posts often reflect short-term goals and may not accurately represent long-term behaviours. And the method lacks opportunities to elicit deeper understanding through conversation and shared meaning (Branthwaite and Patterson, 2011). Therefore, qualitative research using social media should be interpreted with consideration of both its advantages and limitations.

In the context of under-researched cosmetic user groups, such as BPS consumers, social media provides a valuable avenue for exploring their makeup application practices and underlying motivations without the logistical complexities of recruiting and organising individual interviews. For instance, YouTube makeup tutorials created by BPS content creators offering both visual and auditory data for analysis can be used as primary material. Although such materials may not fully represent the everyday practices of the broader user population, they nevertheless provide valuable insights and can serve as a foundation for subsequent, more detailed primary data collection.

Aim

This study aims to explore the intersection of beauty, social disability, and empowerment, focusing on BPS women who use makeup and share their experiences through YouTube tutorials. It also seeks to identify product features of practical significance for developing universal design principles for cosmetics.

Method

The study analyses ten makeup tutorials shared via YouTube as the largest at the time of research (2021-2022) platform for posting such material (Ceci, 2024). A variety of authors/sources was set as a priority in order to achieve good representation, hence a limit of three video tutorials by a source was set. The selection of tutorials aimed to cover as many makeup products as possible. YouTube-generated transcripts were coded using NVivo software and analysed following the six-step thematic analysis framework discussed in more detail in the section dedicated to articles 4 and 5 (Braun and Clarke, 2008). Content analysis of other elements of the tutorials, such as the colour of the makeup products used and the glimpses of home environment or other people, was also conducted. The findings were discussed in the interdisciplinary context of cosmetics' materiality, media studies, and social disability.

Results and discussion

Three major themes emerged from the analysis of the transcripts and content of the video material (Figure 3).

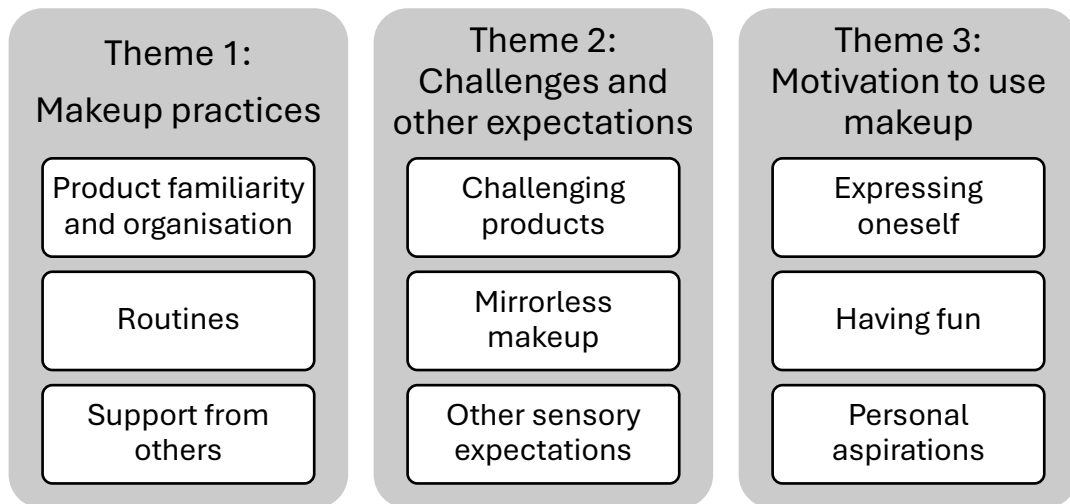


Figure 3. Themes and subthemes emerging from the thematic analysis of the video material (Daniels and Khadaroo, 2024: p.208).

These three themes were further analysed in the context of published research in multiple domains. From media studies perspectives, the success of beauty vloggers in general has been credited to their careful positioning as ordinary experts who can be trusted (Tolson, 2010; Foster and Pettinicchio, 2021). The BPS vloggers in this study also positioned themselves as ordinary experts, covertly demonstrating to sighted audiences that beautification is not defined by vision alone. The sensory stimulation and enjoyment they referred to were very important, too, enforcing the notion of the self-care and self-agency. The findings were also examined through the critical lens of beauty as a socially constructed phenomenon, intertwined with identity and cultural norms often reinforcing inequalities (Mears, 2014; Sarpila *et al.*, 2020; Kuipers, 2022). The analysis acknowledged these debates and discussed the tension between consumption and accessibility, and personal gains and representation. In doing so, the article questioned established single discipline assumptions and argued that beautification and the widespread use of makeup cannot be meaningfully judged through a binary lens. Instead, the analysis highlighted the complexity of human engagement with beauty and appearance management more broadly (Adam and Galinsky, 2012; Hamermesh and Abrevaya, 2013). In the context of disability, the study emphasised inclusivity as an overarching aim and called for broader research and discussion on disability rights and aesthetics.

Finally, whilst recognising that social media usage encourages higher consumption, the study highlights the BPS vloggers' other motivations for participating and posting, such as to challenge the society's ableist assumptions, to increase disabled people's representation, and to support others. These findings corroborate other studies on

disability representation in social media; hence the outcomes point to the need for a nuanced approach when researching this topic (Seo and Jung, 2020; Södergren and Vallström, 2022).

Methodological critique

Selecting YouTube video tutorials was an appropriate choice at the time of research due to YouTube being the most used digital media platform for such content, whilst the selection criteria offered a reasonable representation of sources, professional and nonprofessional. The content of the selected ten tutorials reached data saturation in terms of the emerging themes and the range of makeup products used. The thematic analysis was iterative because the researchers did not have prior understanding of the topic or familiarity with BPS lifestyle. Overall, the results were based on a high inter-coder agreement which was considered a strength of the study. A limitation of the sample is that all featured BPS people were white and from English-speaking countries, hence the conclusions cannot be generalised globally. However, the validity of findings was strengthened through triangulation with the very limited number of published peer reviewed studies in this field. A strength of this study is its theoretical interdisciplinarity, which was further drawn upon into the discussion and conclusion for the purpose of highlighting the complexity of the topic.

Contribution

The core contribution of this article lies in focusing on under-researched and under-represented group of makeup users. It offers a critical analysis of a unique topic and contributes to several disciplines of relevance: media studies, social studies of beauty and aesthetics, and disability studies and representation. It also calls for more research in this field as a way of improving representation and public awareness and tackling social disability. Finally, it highlights the transformative potential of makeup and the opportunity to expand the definition of beauty to include multisensory experiences.

This publication also represents the next step in the author's personal research journey towards interdisciplinary-based expertise. Within the collective contribution of the whole body of research, this publication highlights most strongly that materials science should be ultimately tasked with facilitating human wellbeing in the broadest sense. To support this notion, the article creates an interdisciplinary space for further integration of insights from materials science, social science, and multi-sensory aesthetics to guide future research agendas.

Contribution and impact

Academic and citation impact

Articles 1–5 were published in the *International Journal of Cosmetic Science*, a peer-reviewed and globally recognised journal launched in 1979 by the UK and French Societies of Cosmetic Scientists, as the two of the oldest and best-established professional bodies supporting research and innovation in the cosmetic and related industries. The journal's stated aim is:

“Bridging the gap between fundamental and applied cosmetic science and dermatology, bringing readers high quality interdisciplinary research in the development of skin and hair care ingredients and formulations”

(International Journal of Cosmetic Science, nd).

Although published in a specialised journal, the first three publications have been cited by peer-reviewed research publications from diverse areas of research, including computer modelling of hair surface tribology, computer vision projects related to hair classification, and hair growth interventions. According to Google Scholar, to date these articles have received a combined total of 43 citations. The review article is the most cited, which aligns with the common trend of review articles being sought after frequently by other researchers. Notably, in addition to the technical publications, this review has also been cited in social science research on hair and identity, thus illustrating that discipline boundaries are permeable. This citation record highlights the potential for interdisciplinary research to generate knowledge and innovation that are both technically sound and culturally sensitive. A table with the citation counts at the time of writing of this thesis is presented in Appendix 1.

Industry and professional practice impact

Beyond citation metrics, the hair-related research publications are relevant to professional practice in dermatology and trichology and cosmetic industry innovation. Following the publication of the hair taxonomy articles, research sponsorship contracts between the UAL and Unilever Hair Research and Development have been signed, including a fully funded PhD studentship, which aims to develop an interdisciplinary methodology for expanding the knowledge of curly hair's technical parameters, whilst incorporating behavioural data. Unilever is the world's third largest company in the haircare market, and the global market share of the Unilever's top four best performing haircare brands that can draw on this research (Sunsilk, Dove, TRESemme and Clear)

is 8.8%. This ongoing collaboration signifies the potential economic impact of the research leading to the taxonomy framework.

Furthermore, the author has shared the curly hair taxonomy articles at private membership trichologist groups and received support and recognitions from expert researchers such as Dr Crystal Porter, Mane Insight Consultancy and Association of Professional Trichologists USA, and Dr Bessam Farjo and Iain Sallis, co-founders of International Trichology Congress, UK.

“The gap in knowledge when it comes to serving the needs of people with curlier hair types is large. The effort you and your team have made to provide a framework is commendable. Congratulations!!”

Porter, C. (2024) Email to Gabriela Daniels 21 March.

“We would be honoured if you would share your findings with us in an ITC Web talk, it sounds like a fascinating topic!”

Sallis, I. and Farjo, B. (2023) Email to Gabriela Daniels 2 February.

Cultural impact

The sixth and final study was published in the *Critical Studies in Fashion and Beauty (CSFB)*, a journal with an arts and media orientation. The following statement sums up the journal:

“The CSFB engages analytically, critically and creatively with fashion and/or beauty. The journal actively fosters more diverse and inclusive perspectives within the field and encourages innovative theoretical and methodological approaches...”

(Critical Studies of Fashion and Beauty, nd)

The acceptance of the article signifies the recognition of interdisciplinary research, presented in this PhD more broadly, as a valuable framework for addressing complex issues and merging subject domains.

Firstly, the key themes of this project were presented at a symposium “Beyond the Visual: Non-Sighted Modes of Engaging in Art” (Wellcome Collection, 2022). Following this event, the author was invited to contribute and be featured in The Cult of Beauty exhibition curated at the Wellcome Collection, London which ran from October 2023 to April 2024 (Wellcome Collection, 2023). The author advised on the selection of exhibits demonstrating successful design adaptations of cosmetic tools and packaging for the

disabled consumer and was recorded in conversation with a blind artist and makeup enthusiast discussing the motivation for makeup use (Figure 4). According to the Wellcome Collection Assistant Curator, (Rose, 2024), in the first seven weeks after opening, the exhibition attracted over 45,000 visitors and was reviewed positively in articles in The Observer, The Guardian, CNN Style and Financial Times. These research dissemination activities illustrate the public and cultural relevance of interdisciplinary research into cosmetics, and how widely the above project has contributed to conversations around beauty, cosmetics and inclusivity.

The interdisciplinarity of this body of work defines its contribution to cosmetic and other fields of research such as disability studies, as well as to professional practice, industry, and cultural discourse.

The different studies have also been reflected in curriculum development and teaching. The critical review article is routinely used by the author in specialised BSc and MSc teaching due to its comprehensive and structured content, as well as by the Language Development Centre as a model for the critical scientific analysis. The remaining hair studies are commonly read and cited by students in various assessments too.

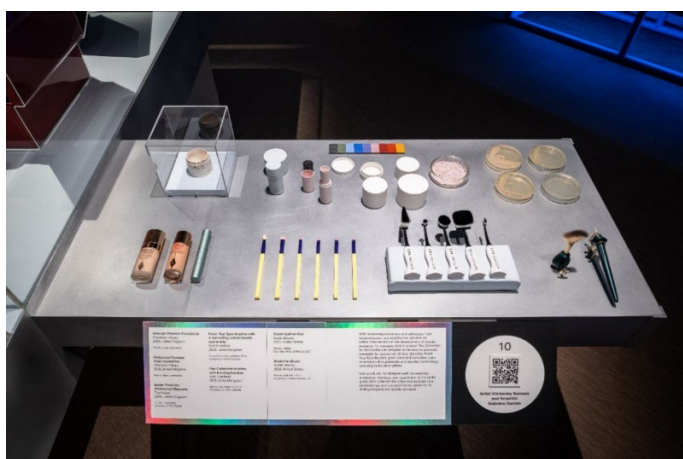


Figure 4. Exhibit 10, The Cult of Beauty Exhibition: Artist Kimberley Burrows and cosmetic scientist Gabriela Daniels discuss accessibility and beauty (Photo from The Cult of Beauty, Wellcome Collection/ Benjamin Gilbert, 2023).

Framework for interdisciplinary research in hair and cosmetics innovation

The materiality of hair and cosmetics, and their recognised personal and social significance, offer strong potential for IDR. Building on the analysis and synthesis of all study outcomes, this body of work further advances IDR combining cosmetic and social

sciences by outlining the difference between theoretical and methodological approaches and proposing a methodological framework for the latter.

Theoretical interdisciplinarity

The rationale for adopting theoretical interdisciplinarity, as well as its application across diverse fields of research, has been extensively discussed in the general theoretical introduction of this thesis and within the individual study-specific sections. The principal contribution of this PhD thesis lies in foregrounding the interdisciplinary perspectives embedded within the constituent studies and articulating their respective contributions. In doing so, this research advances and refines new forms of interdisciplinary cosmetic knowledge that collectively enrich the broader body of scholarship represented by this thesis.

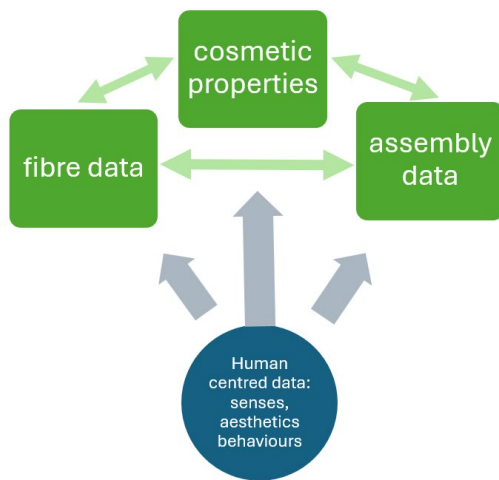
Specifically, the personal and social significance of hair is examined in depth by drawing on core social science disciplines and synthesising insights from multiple sources. Social and psychological studies related to textured hair and hair more generally are discussed within the hair taxonomy articles whilst their relevance to establishing more effective technical hair testing methodologies has been explicitly outlined. Similarly, in the BPS makeup tutorial article, makeup use is explored through the theoretical frameworks of media and disability studies and is further conceptualised using constructs such as *aesthetic capital* and *multisensory aesthetics*, thus positioning the topic in a new interdisciplinary space.

By demonstrating the high relevance of the theoretical positioning of these disciplinary intersections to cosmetic research, this thesis identifies relevant and complementary cross-domain perspectives focused on positive user outcomes within wider social, aesthetic, and wellbeing contexts. It can further be argued that theoretical interdisciplinarity facilitates the emergence of more nuanced and integrative understandings that seek and draw upon shared ground, and pursue practical and holistic solutions, which is one of the core aims and strengths of IDR.

Methodological Interdisciplinarity

Methodological interdisciplinarity could be broadly defined as a framework that seeks to integrate distinct research methodologies. The foundation of the framework, based on the research represented in this PhD, lies in integrating two methodological paradigms: materials science, which is primarily deductive, aiming to theorise, test, and synthesise; and social science, which is inductive, seeking to explore and explain phenomena. To systematically combine these approaches, the conceptual grounding of mixed methods

research has been adopted. Mixed methods intentionally integrate quantitative (deductive) and qualitative (inductive) research. Widely recognised for its ability to generate richer insights into complex phenomena and provide methodological flexibility, mixed methods align well with the needs of IDR in cosmetics.



In developing the interdisciplinary methods framework, the following key considerations and decisions typically applied in mixed methods research have been considered:

- implementation (the time order of the data collection and analysis);
- priority (which method is more significant in data volume and for achieving the aim);
- integration of outcomes (at data collection, analysis or interpretation);
- theoretical perspective (whether it is explicit or implicit)

(Creswell, 2004; p.10)

Guided by these considerations, two framework variations of interdisciplinary methods are outlined below. These variations are further explained in the context of the studies included in this thesis. However, the framework is intended for the application in further IDR by the author too.

Articles 1 and 2 exemplify the parallel study design approach (Figure 5), whereby human data in various forms (e.g., surveys, sensory evaluations)

Figure 5. Interdisciplinary Parallel Study Design

are collected

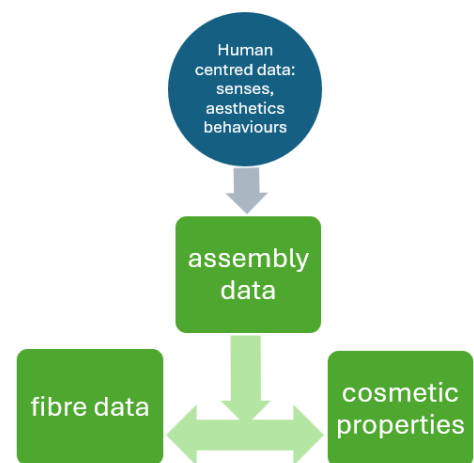


Figure 6. Interdisciplinary Sequential Study Design

independently but intended for integration in the analysis and interpretation alongside hair fibre data. This design is not prescriptive regarding the exact temporal sequence or the integration of human-centred outcomes, and it assigns priority to material science experimentation, both in theoretical orientation

and data volume. What marks this framework as interdisciplinary, is that the methodology draws explicitly on the theoretical and integrative contributions of human data from the start, rather than being confined to a post-material experimentation confirmatory role, akin to product evaluation studies commonly reported in technical and scientific cosmetic literature.

Articles 4 and 5 collectively illustrate a comprehensive human-centred sequential study design (Figure 6) that is intended for further integration into the testing of hair tresses, thereby informing directions for more fundamental material science research. This IDR framework establishes explicit implementation principles by emphasising that human-centred data are first required to guide specific material science investigations related to cosmetics, particularly hair research. While remaining flexible regarding prioritisation and integration, this framework is explicit about the interdisciplinary theoretical underpinnings of the project.

Conclusion and future directions

This body of research represents the integration of social science theories and research methodologies with materials research focused on cosmetics, thus aiming to expand the cosmetic research field and support innovation. The principal contribution of this PhD thesis is two-fold: foregrounding the interdisciplinary perspectives embedded within the constituent studies and advancing new forms of interdisciplinary cosmetic knowledge that collectively enrich the broader body of scholarship.

Specifically, by drawing on social science disciplines and synthesising insights from multiple sources, the personal and social significance of hair is examined and integrated in hair-testing focused studies. The emphasis is on evolving technical research and innovation in conjunction with methodologies for exploring human behaviours. By reviewing and critiquing the individual studies, the thesis acknowledges the disciplinary boundaries and the principal epistemological differences of the represented fields. It then scientifically connects all the studies and demonstrates how combining science and sensitivity to social and cultural constructs can create more nuanced and innovative research.

The strength of this body of work lies in its methodological rigor, demonstrated through the explicit justification and critical evaluation of data generation and data analysis methods. The adoption of IDR as a guiding framework highlights both the retrospective and prospective contributions of the research. The thesis goes further and articulates an interdisciplinary methodological framework intended to provide a blueprint for carrying out further research in the field. However, whilst theoretically justified, the proposed methodological framework requires further empirical testing. Hence, this body of work offers only a preliminary window into the integrative opportunities such an approach affords. To develop and test further the IDR framework, research in other related cosmetic fields such as skin care, makeup formulation and testing will be necessary.

Finally, the work also highlights that interdisciplinarity could be achieved at a purely theoretical level even when a research project clearly aligns with an established methodological domain. This contribution is of relevance to cosmetics research, as it expands its scientific foundations by integrating insights into the social and personal effects of products on individuals. Moreover, it also encourages the integration of materials and biological science into relevant domains of social science, since objective measures and observations can provide an explanation and be supportive in modifying behaviours and consumption in a positive way. The theoretical interdisciplinarity thus offers the opportunity to pivot cosmetic and social research towards more holistic understanding of the human experience and better alignment with wellbeing goals.

It is anticipated that this work will be extended in the near future in several directions. Through interdisciplinary parallel studies, textured hair's specific management challenges and related instrumental measurements at the fibre and assembly levels will be explored. This field of research requires separation from the more general curly hair research, as the research so far highlights the stronger cultural impact on haircare and management practices. Using mixed methods research, further explorations of the behaviour and well-being of less well-studied consumer groups are also planned, specifically consumers with greying hair (following global demographic trends) and consumers with disabilities or neurodivergent characteristics.

Appendix 1.

Title	Year of publication	Google Scholar citations
How different is human hair? A critical appraisal of the reported differences in global hair fibre characteristics and properties towards defining a more relevant framework for hair type classification	2022	21
Artificial Intelligence in hair research: A proof-of-concept study on evaluating hair assembly features	2021	12
Measuring the frequency of consumer hair combing and magnitude of combing forces on individual hairs in a tress and the implications for product evaluation and claims substantiation	2018	7
Taxonomy for the assessment of the subjective experience of curly hair manageability	2024	2
Towards a taxonomy for assessing and classifying the needs of curly hair: A mixed method, ethnographic and quantitative data study	2024	1

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