FeatherHair: Interacting with Sensorized Hair in Public Settings

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ABSTRACT

Human hair opens up new opportunities for embodied interactions that build on its unique physical affordances and location on the body. As hair has high socio-cultural significance, the design of hair interfaces is coupled with social and personal needs. Albeit this makes field investigations indispensable, they are missing from prior work. We present a fabrication approach for gesture-controlled hair interfaces that are robust enough to be deployed in the field. Our approach contributes sensorized feather hair extensions that combine capacitive and piezoresistive sensing. Their tactile properties make the interface blend seamlessly with human hair. We furthermore contribute results from a field experiment where participants gained first-hand experience in various social contexts. These show how hair-based interactions have great potential moving beyond planar touch gestures whilst their social appropriateness is context-sensitive. We synthesize the findings into design implications that ground the future design of usable and socially acceptable hair interfaces.

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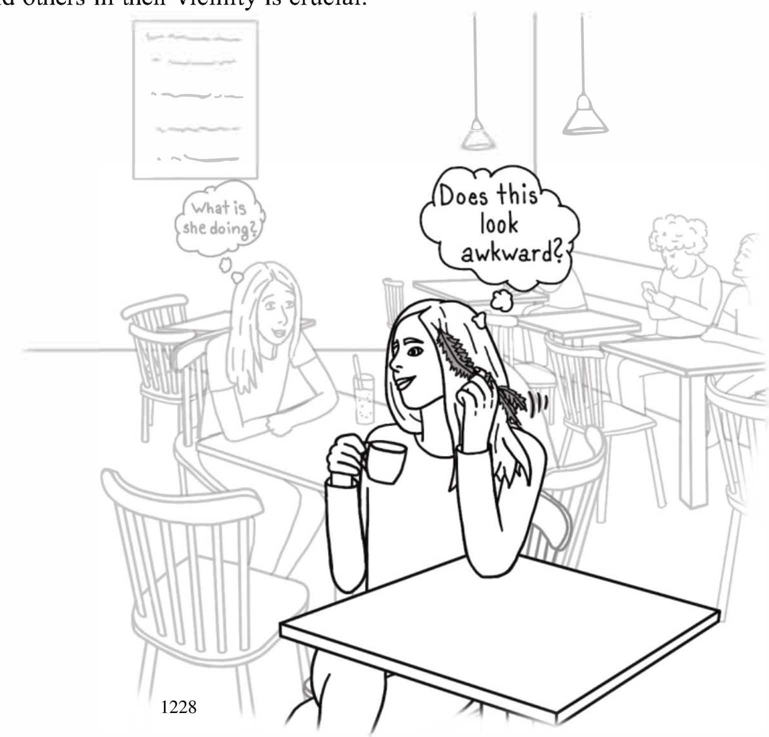
INTRODUCTION

Novel materials and fabrication techniques have opened up new, creative ways interfacing the human body surface with technology, including interactions on skin [13, 14, 21, 34, 42, 43], nails [12, 18, 41], and hair [7, 38, 40]. Hair opens up an exciting interaction space as it is also malleable, extremely versatile, and affords being embedded in natural gestures in very unique ways. Yet, these opportunities are so far little explored. Hair has high socio-cultural significance [30, 31, 36], which creates the risk of misunderstandings, irritation or social tension. Thus, the perception of hair interfaces by users and others in their vicinity is crucial.



To gain such insights, field studies are an essential tool. Yet, current gesture-controlled hair interfaces lack robustness. Thus, user studies outside of laboratories and in real-world settings remain a major challenge, which prevents researchers from running experiments in the actual social context and ultimately impedes hair interfaces from making a direct impact in daily lives.

We contribute FeatherHair, an approach for creating gesture-controlled hair interfaces that are robust enough to be deployed in field studies. We demonstrate how FeatherHair supports real-world deployment by conducting a field experiment traversing various public spaces. Contributing unique insights from semi-structured interviews with our participants, we synthesize four concrete design implications for usable and socially acceptable hair interfaces.

We introduce a novel hybrid sensing technique for interactive hair combining capacitive and piezoresistive touch sensing. Featherhair consists of feather hair extensions, which are sensorized using polymerization [9, 34]. This is a chemical process that incites conductive polymers to form around individual fibers, in our case a feather's barbs and barbules. It allows the feather to retain its malleability and to softly blend in with natural hair.

We deployed FeatherHair in a field experiment designed as a walking route across diverse public settings. To the best of our knowledge, this is the first field experiment reported in HCI literature that allowed participants to gain hands-on experience interacting with a gesture-controlled hair interface in actual social contexts. Based on semi-structured interviews with seven participants, we identify crucial pointers to both, pragmatic and usability-related, as well as social and emotional challenges of hair interfaces.

Drawing insights from our field deployment, we contribute design implications for usable and socially acceptable hair interfaces. They add to the body of prior insight (gathered exclusively in the lab), by covering (1) wearability of hair interfaces while in motion and outside, (2) suitable gestures for various social contexts, as well as adapting hair interfaces to (3) diverse users, and (4) varying social contexts. Most significantly, we motivate how future hair interfaces should be designed neither as one-fits-all nor as general purpose devices.

In summary, our fabrication approach for deployable, interactive hair along with insights from our field experiment open up new paths towards hair interfaces for everyday wear.

RELATED WORK

Leveraging a variety of input and output techniques, hair interfaces have been explored for various interactive applications. For instance, touch sensing hair [7, 17, 40] uniquely affords unnoticeable gesture commands, e.g., to act as a security device [40]. Shape or color change [7, 20, 37] can turn hair into a social display [7, 20]. Positioned directly on the head, hair interfaces are also a promising means to turn tactile sensations [2, 3, 7] into haptic and visual notifications [7]. While hair interfaces remain relatively sparsely researched, taken together, these first works illustrate the potential of hair as an interaction space.

Hair Interfaces in Public Spaces

As part of the human body, hair is also potentially problematic as an interaction space because it is socially and culturally loaded and there is a risk of making normative assumptions when designing hair interfaces [32]. Therefore, we strongly argue for involving users early-on in the design process. So far, only few existing hair interfaces have been tested with users [7, 38, 40]. Amongst those, only two works, HäirIÖ [7] and Hairware [40], provided participants with hands-on experience with prototypes (touching, stroking), and only users of the former were given the option to wear it. All prior studies were conducted in lab settings. Even research on social aspects (e.g., social acceptability) is often confined to lab and online settings [16]. Yet, social aspects of interactive technology are highly context-dependent, as they relate to co-located social practices [39], location and audience [28], or aesthetics [26]. Field studies are an effective method that allows the participants' to develop realistic and profound opinions about the interaction [1, 16, 28]. Thus, accounting for hairs' socio-cultural significance [30, 31, 36], the field study presented as part of this pictorial contributes a crucial next step.

Sensorizing Hair & Hair-like Structures

Hair is exciting as an interaction space because it is soft, versatile, and malleable – characteristics that should be preserved when it is sensorized. Prior techniques on soft sensors, e.g., printing of conductive traces onto soft materials [15] or casting conductive soft substrates [42] are inapplicable to micro-thin structures such as hair. Similarly, infusion with conductive liquids [25] is not promising due to practicality. An applicable alternative is braiding or weaving in conductive yarn or wires [7, 10, 17], which, however, may affect tactile qualities and flexibility. Passive chemical treatments allow to create (body) hair that reacts to changes in a magnetic field [2, 3] or temperature [37]. Extending this line of thought, chemical treatments that create hair-like conductors are promising.

Vega et al. present an approach to chemically metalize hair extensions on which they successfully demonstrate capacitive touch sensing [40]. However, the authors also note how their user study had to be "in the same laboratory under the same conditions (temperature, humidity and pressure)" due to the influence of geotemporal factors on *capacitive touch sensing*. Recently, polymerization, a chemical treatment that has been used, for instance, on diverse materials [9, 34] has been demonstrated on feathers: Briot et al. [6] incorporated polymerized feathers into an interactive art installation featuring capacitive touch sensing. We demonstrate combined, *piezoresistive and capacitive sensing* on polymerized feather hair extensions to enable robust gesture detection on interactive hair.

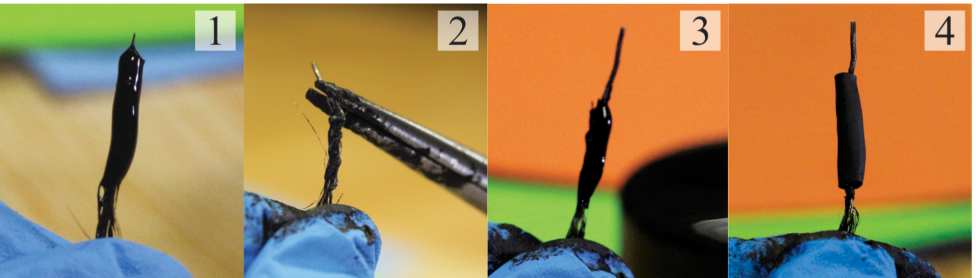
FEATHERHAIR

FeatherHair realizes robust gesture detection on sensorized hair using a hybrid approach that combines capacitive and piezoresistive sensing. Our FeatherHair prototype consists of several strands of feather hair extensions that we modified to obtain conductive properties and attached to a microcontroller board. Feather hair extensions (made from rooster feathers) are compelling due to their tactile qualities which are close to human hair and because they can be subjected to polymerization.

We used commercially available feather hair extensions (FeatherLocks, 25–40cm length, 3 bonded strands each) and made them piezoresistive using polymerization. Polymerization incites conductive polymers to form *in-situ*, i.e., around individual natural fibers, augmenting them with electrical functionality [9]. Briot demonstrated that feathers possess the potential to be polymerized [5, 6]. In contrast to hair, the characteristic "downy" structure of feathers allows the conductive polymers to form around the feather's individual barbs and barbules. When the feather is then manipulated (e.g., stroked or pressed), they compress against each other and towards the rachis and a change in conductivity occurs: piezoresistive sensing becomes possible.

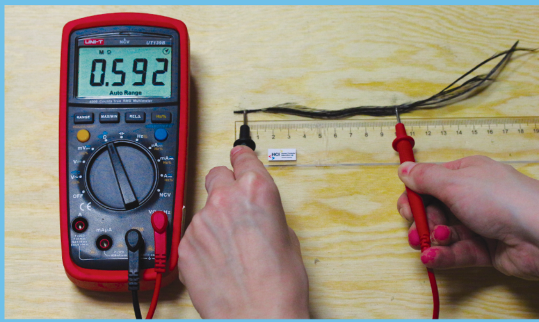
We implemented our prototype on an ItsyBitsy M0 Express, a commercially available microcontroller board that balances functionality and size. We detail on the polymerization process on this page's right side, and on the overall set-up and hybrid sensing on the next page.

We add **solderable connectors** to the polymerized feathers. A connector is made of several layers: 1) The innermost layer consists of bare conductive which is applied to upper hollow shafts of the feathers, acting as conductive adhesive. 2) A wire is then wrapped tightly around the hollow shaft covered by the adhesive. The protruding end of the wrapped wire serves as the solderable connection point which connects the feather to the microcontroller. 3) Another layer of a conductive adhesive ensures that the conductive parts are tightly connected. 4) A shrinking tube insulates the inner layers.



We soak the feathers first in H_2O_2 (1), then in a pyrrole dilution (2). After adding pulverized iron (III) chloride (3) to the dilution, the feathers turn black (4). This indicates successful polymerization.

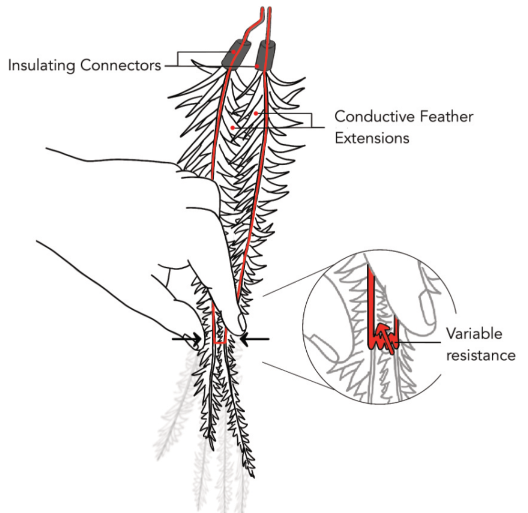
The polymerized feathers exhibit a mean resistance of 0.5 MΩ (SD = 0.3 MΩ), measured with a multimeter on a length of 10 cm once for each feather.



Polymerization Process

Feathers are more challenging to polymerize than other natural fibers, e.g., cotton. Thus, we extended the procedure presented by Honnet et al. [9] by adding multiple iterations of polymerization and a pre-treatment step.

- Prep. We pre-treat the feathers by bathing them in 30% hydrogen-peroxide (H_2O_2) for 15 Min. This removes grease and primers and prepares the feather's surface. Then, the feathers are rinsed in cold water.
- Step 1 Next, we soak the feathers in a mixture of pyrrole (6.25ml) and water (250ml). We obtained best results using 25 Min for 1st iteration, and 15 for three subsequent iterations. Each iteration increases conductivity.
- Step 2 We pulverize 2.5g iron (III) chloride powder using a pestle.
- Step 3 The iron (III) chloride is added to the pyrrole dilution and slowly stirred for 30 Min. The mixture is now oxidizing and conductive polymers form around the feathers' fibres, causing the feathers to progressively blacken with each iteration.
- Step 4 The feathers are rinsed in cold water. Steps 1-4 are repeated three more times (4 iterations in total).

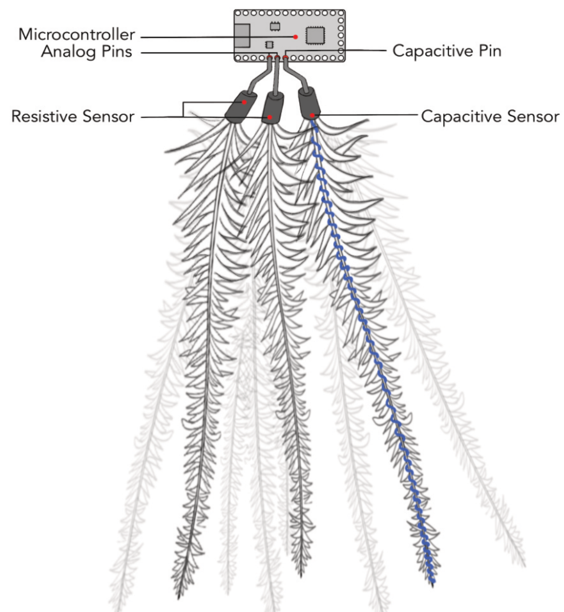


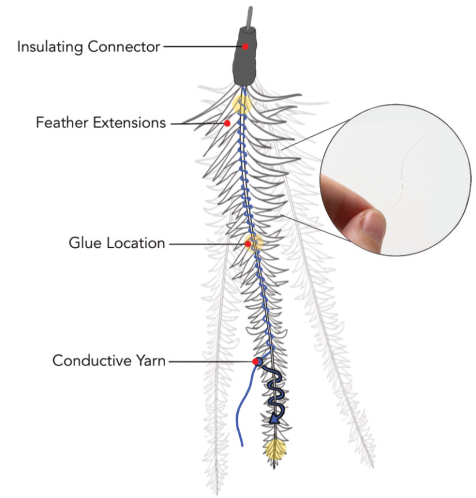
Piezoresistive Sensing

Piezoresistive touch sensing measures a variable resistance which decreases when force is applied to the sensor [29, p. 544]. FeatherHair's piezoresistive sensor consists of two groups of feathers. Each is made of 4-5 conductive, piezoresistive feathers. This makes the sensor thick enough to be easy to grasp and squeeze whilst it is still small enough to not look clumsy. The individual feathers of a group are kept together at the end of their hollow shafts through a connector (cf., previous page). One group is connected via the connector to an analog output pin, the other one to a neighbored analog input pin of the microcontroller. We measure the variable resistance across one direction, applying constant DC voltage to the analog output pin. When both sensor parts are pressed together, the piezoresistive feathers make electrical contact. This changes the potential that we measure at the analog input pin, indicating the occurrence of touch.

Hybrid Sensing

FeatherHair combines capacitive and resistive touch sensing to realize robust gesture recognition [33]. The feathers realizing the hybrid sensing are connected to a commodity microcontroller. Here, we used an ItsyBitsy M0 Express. The ATSAMD21 Cortex (M0) board is tiny, lightweight, and has 11 12-bit analog inputs and 7 hardware capacitive touch pins. The latter realize capacitive sensing in hardware, not requiring external resistors for the implementation of capacitive touch sensing. The microcontroller measures the hybrid data at a 10 Hz sampling rate where each sample is the average of 5 individual measurements. Hereby, it uses spatial multiplexing with two analog pins for piezoresistive and a separate hardware capacitive touch pin for capacitive sensing. We use CircuitPython, a Python-based programming language with hardware support, for the firmware implementation. This setup is the core of the physical prototypes (cf., next page).



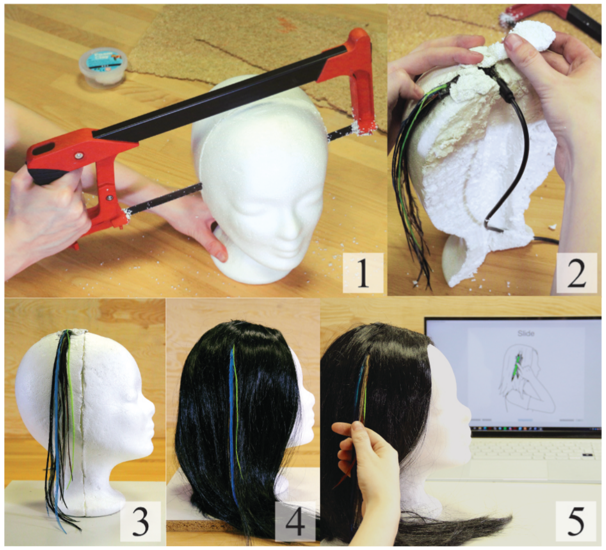


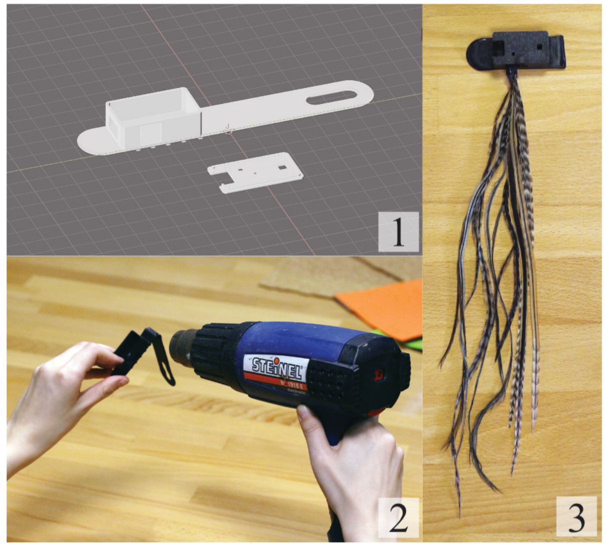
Capacitive Sensing

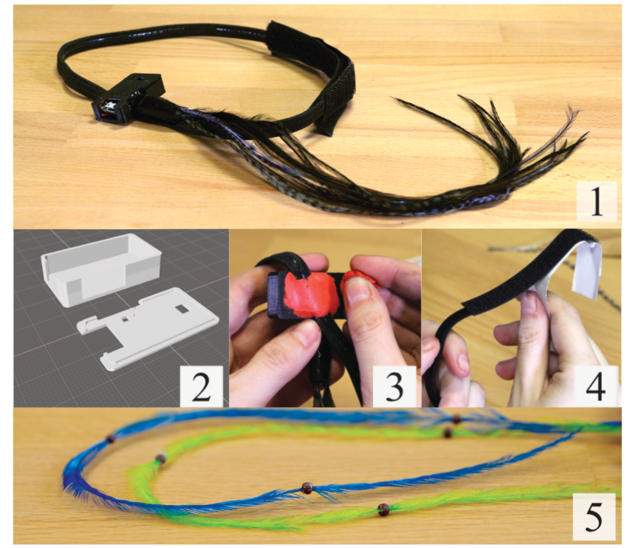
Touch sensing is implemented using self-capacitance, measuring a change of capacitance over time when a conductive object approaches the sensors' conductive plate [8]. To realize this conductive plate, we opted for an alternative approach to polymerization since preliminary experiments have shown that the resolution of capacitive sensing through polymerized feathers was insufficient. Thus, we used very thin conductive yarn (Bart & Francis Inox (steel) 0.035 mm) that guarantees a high conductivity. The yarn is wrapped tightly around one feather of the feather bundle and carefully fixed with transparent glue at the top, middle, and bottom. This prevents it from slipping from its place. A connector on top of the feather's hollow shaft allows to connect the capacitive sensor directly to a hardware capacitive pins. By measuring the capacitance steadily on this pin, we can infer the occurrence of touch through an increase of capacitance.

PHYSICAL PROTOTYPES

We embedded the raw circuit presented in the previous section into three physical scaffolds. We detail on their construction and specific use in the context of this work below. During the design process, key challenges involved unobtrusiveness of the appearance, easy attachment, and wearability for versatile types of users.







Data Collection and Illustration: The Demonstrator

The microcontroller is integrated within a styrofoam head that was cut into two halves (1) and fixed with insulating foam clay (2). Pulling the protruding feathers (3) through a wig, the technical components of the prototype remain hidden (4). This shows the potential of hair interfaces to seamlessly blend in with hair if the technology would be fully miniaturized. We use this prototype as part of the data collection (cf., next section) to demonstrate the gestures (5). Contrary to the wearable prototype, it removes the influence of the skin's proximity on the capacitive measurements. Collecting and comparing data for both types of prototypes, we evaluate the robustness of the presented approach.

Quick-and-Easy Attachment: Wearable V1

For the first iteration of the wearable prototype, we embedded the microcontroller within a 3D-printed PLA case that has a hair clip integrated (1, 3). The print was brought into the shape of a hair clip through the application of heat (2). The hair clip allows for easy attachment to the user's hair. However, when we used Wearable V1 for the data collection study (cf., next section), we found that the hair clip does not stick at its place for smooth hair. Furthermore, we observed that the feathers missed haptic landmarks that allow to locate them within the hair. This resulted in participants having difficulties to identify if they were interacting with the interface properly. We addressed both observations in a second design iteration (cf., "Wearable V2").

Robustness and Detectability: Wearable V2

Wearable V2 is designed to solve both the problem of missing haptic guidance and a stable attachment to hair. Hereby, we embedded the microcontroller within a tiny 3D-printed PLA case (2) that is attached to an elastic hair band (1, 3). Straps of velcro tapes (4) make the hair band adjustable in size and a fit for all types of participants. We further attached in total six tiny beads to the two non-functional feathers of the capacitive feather bundle (5) . The beads serve as haptic landmarks. They aim to guide the user's interactions and to make the feathers easier to distinguish from the user's natural hair without weighting it down. Wearable V2 was used for the final field study (cf., Section "Hair Interfaces in Practice").

RECOGNIZING HAIR GESTURES

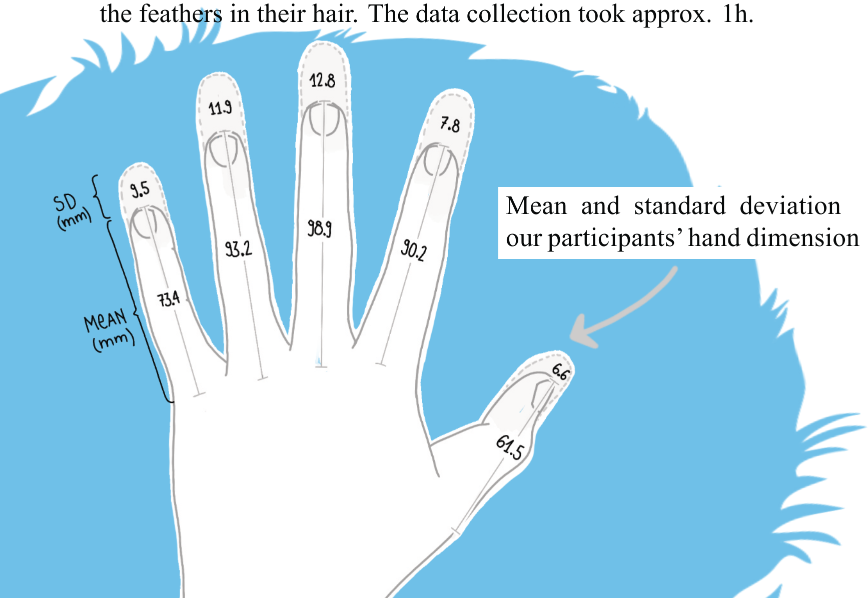
FeatherHair's software component implements gesture recognition using a random forest classifier trained on a data set comprising five gestures. Here, we report on our data collection for which we used the Demonstrator and Wearable V1 (cf., previous section), and provide an overview of our data set and classification approach.

Participants

We recruited 10 participants (5f, 5m, 0d) which were aged between 11 and 76 (M = 34, SD = 23). All of them are right-handed and have different hair structures and lengths (ranging from short and straight to long and curly). For reference, we manually measured the hand dimensions of our participants following the BigHand2.2M approach [45].

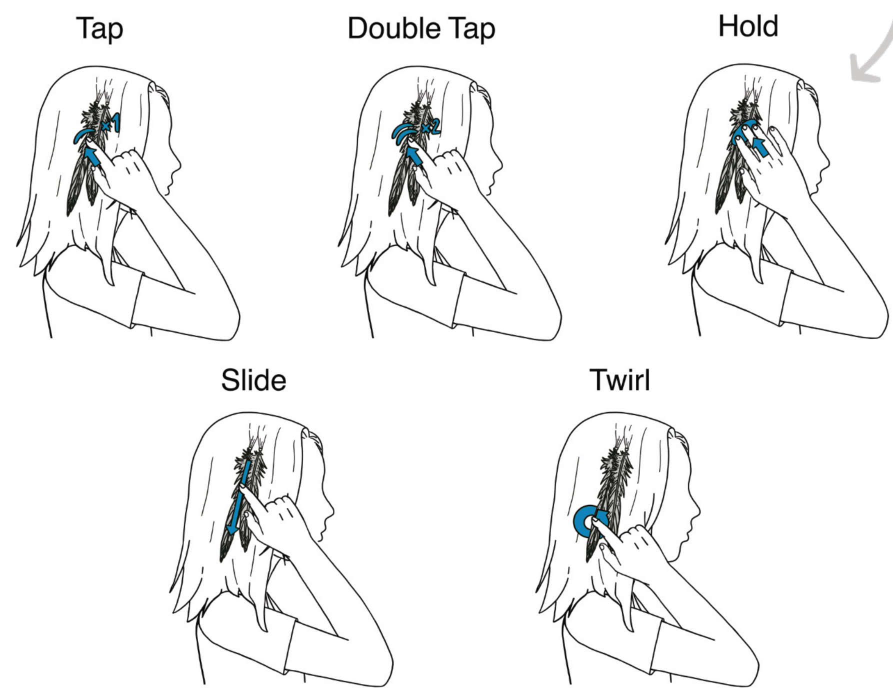
Data Collection

After providing informed consent, participants could familiarize themselves with the gestures and the Demonstrator until they confirmed that they felt confident and had memorized them (approx. 5 Min). Then, we continued with the data collection. Each participant performed 25 trials of each gesture on the Demonstrator and 25 trials on Wearable V1 whilst being attached to their hair. Starting with the Demonstrator, they were prompted to perform one of the five gestures (displayed as illustration on a screen) in randomized order. Our sampling procedure allotted 10 seconds for the participant to perform the gesture and recorded resistive and capacitive data readings at 10Hz. After performing all gestures on the Demonstrator, the participants donned Wearable V1. We continued to record data samples while the participants manipulated and put Wearable V1 on (and off). These are included as noise class in our data set. Again, participants performed 25 repetitions of each gesture in randomized order. A mirror was available to facilitate locating the feathers in their hair. The data collection took approx. 1h.



Mean and standard deviation our participants' hand dimension

Our **gestures** comprise *Tap* as a discrete motion, *Doubletap*, static *Hold*, and two natural hair-based gestures, namely *Slide* and *Twirl*.



Data Set

Our balanced data set comprises gestures of 10 participants. Each gesture was recorded 50 times per participant (25x Demonstrator, 25x Wearable V1). Gestures have a duration between 1.5 and 10 seconds (M = 4.6, SD = 1.2) and are represented as variable-length time series. Each gesture execution is framed by 1 second of further data. In total, the data set includes 5 gesture classes and one class of noise samples. It consists of 3074 samples in total which are approx. balanced across all six classes (750 noise samples). The data set can be retrieved from GitHub under `https://github.com/HCI-Lab-Saarland/FeatherHair`.

Feature Engineering & Classification

We randomly split our data set into a training set (80%) and test set (20%). To avoid information leakage from the test to the training set, we used the data of 8 participants for training, and held back the other 2 for testing. In order to boost the applicability of our model to field experiments, we opted for user-independent gesture recognition using data samples from both, the Demonstrator and Wearable V1. We based our implementation on Sci-kit Learn [27]. First, we created an initial feature set of 40 classical statistical descriptors such as mean, skew, and kurtosis. Then, we performed univariate feature selection that selected the six best features using an ANOVA F-value scoring function on the training set. Most notably, all features are a combination both, the normalized capacitive and resistive characteristics, e.g., reflecting the number of mean crossings for both the resistive and capacitive time series and their correlation coefficient.

We used leave-one-person-out cross-validation on the training set to analyze the performance of various classifiers and models. For the prototype used in our field experiment, we aimed to balance real-time efficiency and accuracy and trained a random forest classifier (n_estimators = 100, unlimited tree depth). Initially, this resulted in an accuracy of 76% on the train set. Based on confusion matrices, we then investigated classification errors. We observed a particularly high error rate for *Twirl* (25% mistaken for *Slide*, and 18% mistaken for *Noise*). To prevent participants' concerns about the system's reliability, we retrained the model for the field experiment with *Twirl* removed and optimized its hyperparameters. This resulted in an accuracy of 89% on the test set (86% on the training set). This indicates that the model is neither over- nor underfitted. It is capable of performing user-independent gesture classification at an avg. time of $4*10^{-5}$ seconds per prediction. The trained model can be retrieved from GitHub (`https://github.com/HCI-Lab-Saarland/FeatherHair`).

FeatherHair (Wearable V2) is attached to the user's hair. It is connected to a hand-held display. The display shows the recognized gesture in textual form: `TAP`, `DOUBLETAP`, `SLIDE`, `HOLD`, `TWIRL`.

HAIR INTERFACES IN PRACTICE

We used FeatherHair (Wearable V2) to conduct a field experiment.

Study Setting & Procedure

We aimed to provide the participants with realistic hands-on experience with the hair interface in diverse social settings. Thus, inspired by [22], we designed a **walking route** as field experiment (see next page). The walk consisted of two guided and one unguided segment, i.e., with and without the experimenter present; participants were prompted by the researcher to perform specific gestures as well as allowed to freely explore. A display connected to FeatherHair (see photo) provided textual feedback of the recognized gesture, making the interaction more realistic without linking it to a specific use case.

After providing informed consent, participants tried out the gestures (which the experimenter demonstrated) until they confirmed that they felt confident and had memorized them (approx. 2 Min). After the training phase, experimenter and participants started their walk. Guided walks (approx. 15 Min) were accompanied by semi-structured interviews (see next page for questions), capturing immediate responses on-site. Upon arriving at the end of the route, we asked follow-up questions that were not yet answered during the walking conversation (5–15 Min). All conversations were audio recorded.

Data Analysis & Positionality

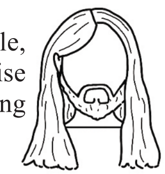
We transcribed the participants' statements and analyzed them inductively and iteratively through several interpretation rounds. With our experiment touching upon both pragmatic aspects (e.g., attachment) as well as personal and emotional ones, we took two different, qualitative approaches: qualitative content analysis (QCA) [23] with an objective focus on usability, and semantic thematic analysis (TA) [4] with a focus on the participant's subjective experience. For categories resulting from the former, we report occurrences with 'n'. For the latter, we discuss themes in-depth and refrain from quantizing. In addition, thematic analysis characteristically builds upon the authors' interpretation to assign meaning to observations. As hair as a research topic is culturally-tied, noting the author's positionality is crucial [32]. This pictorial's authors have mostly lived, learned, and researched in Central Europe and North America, are cis, white, binary, and based at a Western academic institution – where the experiment has been conducted. Since an on-site experiment was considered substantial for the research question, we recruited locals for participation. The authors' background and the participants' similar background shape this work's perspectives on designing socially acceptable technology.

PARTICIPANTS

P1, 25, male, limited expertise on hair styling

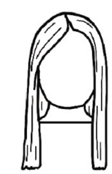
P2, 28, male, no expertise

P3, 26, male, limited expertise on hair styling

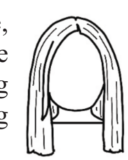


P4, 22, female, some expertise on hair styling, braiding, and coloring

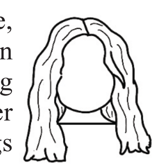
P5, 26, female, some expertise on hair styling and braiding



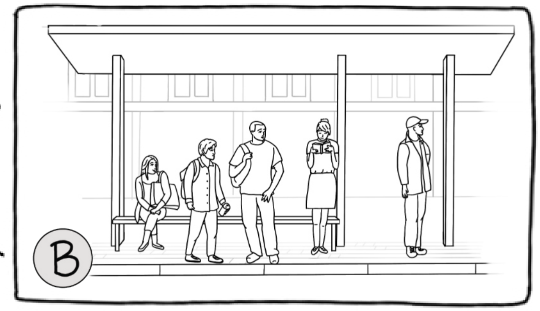
P6, 22, female, some expertise on hair styling and braiding



P7, 25, female, strong expertise on hair styling, braiding and coloring, eager to try new things



The walking route was designed to cover diverse **social contexts**: Populated public spaces (A), quiet outdoor areas (C) and indoor locations (F), as well as a busy bus stop with people waiting (B), a cafeteria (D) and a popular gathering spot (E) where students like to sit and talk.

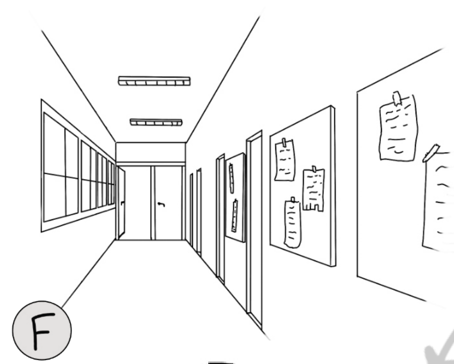


During the first third of the route, the researcher accompanied the participants as part of a **guided walk**. The participants received oral **gesture prompts** at pre-determined locations to ensure that all gestures were tried out in all types of traversed social contexts (including A, B, C). The researcher asked for feedback on how they perceived the interaction in the current context directly after.

Interview questions were asked in a conversation-like manner throughout the guided walks as well as after the unguided walk. The questions included, e.g.:

- *How easy was it to learn the gestures? How intuitive are they?*
- *How (un)natural do the gestures feel (in comparison to how you usually interact with your hair)?*
- *Which problems occur whilst executing the gestures? What causes them?*
- *How (confident) do you feel performing these gestures? Which factors influence this feeling and why?*
- *[...]*

During the second part of the route (denoted by [---]), the participants explored the interaction with the prototype without the researcher. The **unguided walk** ensures that the researcher's presence did not impede representative interactions. The participants received oral and written instructions about **gesture prompts** and the route (A, D, E) beforehand. Their experiences were captured by the researcher through a semi-structured interview afterwards.



During the last part of the route, the researcher accompanied the participants in a **guided walk** whilst the participants were asked to **freely explore** further interaction possibilities with the prototype in diverse contexts (A, C, F) and discuss their thoughts with the researcher in a conversation-like manner.

RESULTS

Here, we present findings from our two-fold qualitative analysis. First, we detail on pragmatic perspectives and usability, then on social and emotional aspects.

Pragmatic Perspectives & Usability

We report on practical and usability related aspects by denoting categories [23] mentioned per participant as n.

Natural, Unobtrusive & Error Prone Movements. All participants noted that the gestures they perceived as 'natural' were least obtrusive and observable. There was, however, disagreement on what was natural. A majority found *Slide* to be the most natural gesture (n=5): *"like a classic 'My hair is hanging in my eyes!', and, bang, you pull it back"* (P3). In contrast, two participants perceived *Slide* as *"conspicuous and unnatural"* (P5, P6). P5 elaborated that, despite being somewhat artificial, all other gestures (*Tap*, *Double Tap*, and *Hold*) were familiar because they resembled common gestures for wireless earphones: the familiarity of the gesture has influence on its perceived naturalness, and thus, unobtrusiveness in a given context. Most participants considered *Hold* least natural and most obtrusive (n=6), and noted that in terms of salience, *Hold* felt *"like raising your arm and waiving"* (P1). Consistent with prior work [43], participants preferred dynamic over static gestures: *"one fluent movement and not, for instance, like 'Hold', where I have to make a static touch. That feels more natural and less awkward in public."* (P1). In contrast, participants found the static *Hold* to provide more reassurance and perceived unintentional activation as less likely: *"[..] if you have to apply a little pressure [then] you actually make a conscious gesture"* (P3). Participant 7 elaborated *"Hold is the most concise gesture if you want to ensure that the gesture is working"* (P7) and suggested it for actions such as calling the police. This highlights how desired characteristics of a gesture may depend on its purpose, and its anticipated frequency of use.

Naturalness of Touch & Haptic Guidance. All participants (n=7) appreciated the tactile quality of the feather extensions: *"You don't feel that there is technology in your hair"* (P5). A majority further noted that they would expect hair interfaces to feel like real hair (n=5). Yet, we also observed that this quality made it challenging for the participants to locate the sensorized feather extensions in their hair, which they also verbalized (n=7). Discovering the interface when worn in natural settings (in contrast to interacting with demonstrators, cf., Hairware [40]) complicates longer gestures such as *Slide*: *"[Slide] is natural, but not that easy, especially if it is tangled with hair"* (P3). Some participants adapted by using the microcontroller's attachment as landmark: *"[..] one indicator at the top, which you can feel relatively easily, and then take the hair and pull it down"* (P2). These observations highlight the importance of designing a trade-off between naturalness, as a desired property for hair interfaces, and the discoverability of the interface within the wearer's natural hair, which can be improved by adding haptic guidance.

Ease & Cognitive Load. All participants were able to perform all gestures whilst walking. None required additional training to learn the set of gestures. One participant, who was left-handed, noted: *"[..] it's ok [..] with the right hand, too, at least for me because it's not complicated movements"* (P6). Yet, participants perceived the gestures' cognitive load differently. Participant 4, who felt at ease performing the gestures, noted: *"You do not have to pay much attention [..] definitely better than something screen-based such as a smartphone, [..] or a smartwatch"* (P4). In contrast, two participants stressed that they would not perform *Slide* while crossing a street (n=2), while a majority emphasized that they found familiar gestures such as *Slide* to require only low attention (n=4). *Hold* was found to be challenging, especially when doing other tasks (n=4): *"[Hold] feels like I would want to stop walking when performing the movement"* (P1). We also noted discoverabiliy of the hair interface to affect cognitive load: *"[if] I always have to search for the interface, which requires some concentration, [..] I couldn't look if there was a car coming"* (P6). Yet, participants, including P6, were also optimistic towards easier-to-locate interfaces: *"just grabbing your hair and pinching it is completely fine, I don't have to concentrate for that"* (P6). Again, this highlights the need for a carefully crafted balance: hair-based gestures that are perceived familiar and natural can potentially lower cognitive load, if the interface is easy to locate while pursuing a primary activity (e.g., walking).

Malleability & Reach. It is common to change hair styles throughout the day, also for a small majority of our participants (n=4). As a result, a hair interface would need to be adaptive and flexible in terms of its attachment, appearance, and placement: *"[..]wear it as fashion accessory? Do I want to wear it as hair strand replacement or extensions? Or do I want it to be unobtrusive?"* (P5). In parallel, adaptive attachment poses a challenge to usability: regardless of placement, the wearer should be able to comfortably reach and interact. One participant, for whom we initially integrated the prototype into a ponytail worn over one shoulder (P1 previous page, right), found it too low to reach comfortably, preferring it closer to the crown. Similarly, others appreciated positions located towards the top and front of the head (P2, P7) which they found to be very natural. Participant 7 noted *"[..] this is natural, but if I have to do it further backward, it gets unnatural*" and suggested to make use of the very first strand of hair to ease *Twirl*. Hair creates unique opportunities for wearable interfaces adapting to the user's momentary aesthetic needs, as it is malleable. Simultaneously, interaction needs to be always comfortable: ideally, the interface is always placed where it is easy to reach, e.g., framing the user's face.

Why Hair? & Further (Interaction) Possibilities. Participants stressed how they liked the bodily integration (cf., Mueller et. al [24]) of the hair interface, especially how it merged with their own hair: *"What I like about it that it is integrated in full hair [..] I can take it together with my hair [everywhere]"* (P3). When encouraged to freely explore, all participants proposed additional opportunities for hair-based interactions that they found desirable and/or intuitive. Suggestions included, for instance, the use of multitouch, making use of variations of the distance between multiple fingers on the hair or the touched area. Two participants each proposed to (gently) pull or rub the hair between the fingers, scratch the head or tear hair. One participant envisioned to create knots and braids acting as permanent switches in the hair: *"Braiding is like some kind of button. If I knot my hair [..] I mute my phone. [..] That would be cool because it is like a switch which you are taking with you"* (P2). This idea collection highlights how hair as material [7] could be leveraged to create even more novel interactions, e.g., moving beyond planar touch.

Social & Emotional Perspectives

Here, we approach social and emotional perspectives using TA [4], reporting on themes relevant to hair interfaces.

Perceived Appropriateness is Context-dependent. Participants generally appeared open towards using hair interfaces in social contexts – as long as it does not distract or involuntarily involve others. Especially in situations where others are not only present, but potentially observing, interaction might be perceived inappropriate: *"one sits together at a table, talking, eating, it can be distracting to watch the vis-à-vis [interacting]. [..] If people don't pay attention to you, sitting in the office or somewhere else, then no one is paying attention to the [interactions] or is triggered by you."* (P4). Two participants shared that the (assumed) technology attitude of whom they are with mattered to them: *"[..]among young people at university, it would not be a problem. [..] When being with the family, where everyone is paying attention how you behave, I would imagine [so]"* (P5). They would feel uncomfortable using a hair interface in front of someone, e.g., elderly or technophobe, who might actively ask about them interacting with their hair. This indicates how the appropriateness of interacting with hair interfaces is context-sensitive.

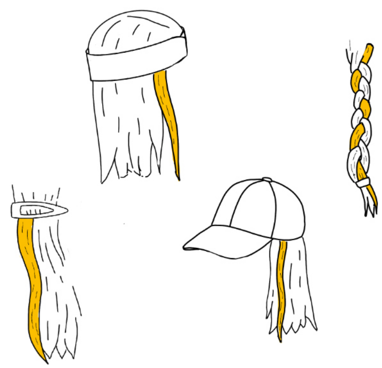
Hair Interfaces tie in with Identity. Hair interfaces, like hair styles in general, relate to how wearers see and present themselves and how they would like to be perceived by others. Conversations with our participants indicated multiple aspects, including gender, but also technology- or fashion-affinity to be decisive. Whether participants felt the interface 'suited' them depended on how they perceived themselves as a person, including but not limited to gender identity. Most attaching form factors (e.g., clips) were found to be not gender-neutral: *"[..] hair clips are rather a thing for women* (P4). Thus, some participants, such as P2, a 28 year old man, were skeptical towards the current form factor and found sleek, 'techy' designs to better match their identity: *"I think that a simple gadget design would be more suitable for me"* (P2). In contrast, P7, a 25 year old woman who describes herself as a non-technophile person, was vehement that a gadget-like appearance would not be a bad match for her background. On the contrary, she felt that the feathers were sweet and would even conform to her style: *"I could imagine walking around [with the interface] outside of this study setting"* (P7). This falls in line our observation that FeatherHair seemed to be perceived primarily as low-tech: *"The interface is rather unobtrusive. I would rather see it as fashionable accessory than something distracting or noticeable"* (P2). *"It is more difficult to make it obviously an interface than a fashion accessory"* (P3). Consequently, the design of hair interfaces needs to incorporate diverse facets of identity, including but not limited to gender. In the case of FeatherHair, especially notions between low-tech and high-tech seemed relevant, which may be anticipated making material choices during the design process.

Touching Hair is Prone to Misinterpretation. Participants showed concern about spectators misinterpreting hair-based interactions. Gestures may indicate being mentally absent in a conversation: *"I want to give others my attention. And when my hand is here [points to his head], [..] I would feel like my counterpart is mentally absent* (P2). Others noted how they assigned social meaning to particular gestures. Participant 2 found *Twirl* to be *"[..] the standard flirting gesture"* (P2), whereas P7 added *"If I start twirling my hair:. it depends on the context, but I might not always want to demonstrate insecurity or playfulness"* (P7). One participant (P4) felt that *Doubletap* might hint towards a quirk when performed too frequently. Similarly, P7 felt that touching hair too often indicates scruffiness. Participants felt strongly that misunderstandings would emerge from the specific circumstances in which the gesture is executed, relating to the degree of personal interaction between the user and the spectator: *"It depends on how you execute the gesture. When I am looking at you in a strange way, then it might appear [suggestive]"* (P6). Two participants noted that they would not care whether they created a suggestive impression with passers-by (P5, P6). These notions indicate that concerns about misunderstandings are more closely tied to the context in which a gesture is performed, while meaning associated with specific movements appears plays a secondary role.

From Surreptitious to Communicative Interfaces. Hair interfaces afford hidden interactions. Participants reasoned about occasions where they would wish to avoid visibly using a device – for instance, using a hair gesture to *"signal my colleague 'Get me out of here!"'* (P2, in a meeting) or to call for help if *"you are on your way home alone, then you can send an emergency call through your hair"* (P7). Comparing to other wearables, e.g., with integrated microphones, hair interfaces may feel more reassuring. For instance, P4 noted *"feathers.. people probably have less concerns than with glasses which have a large interface* (P4). Hair interfaces might also enhance interpersonal touch: *"If [..] your hands are busy [..], you can tell your counterpart 'Can you decline the call?' and [let them] press the interface* (P4), noting how hair was intimate *"you wouldn't let do this everyone, but only close friends and family. [..] I wouldn't let any stranger touch my hair"*. Because or albeit hair is personal, hair interfaces possess manifold potential to enhance interpersonal interactions, from surreptitious communication to trustful collaboration.

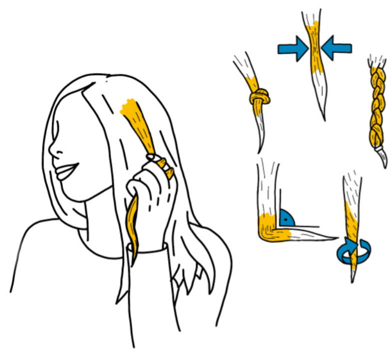
DESIGN IMPLICATIONS

We synthesize our qualitative analysis into design implications that will lay the ground for the future design of usable and socially acceptable hair interfaces. They extend more general design considerations around wearable computing devices and inclusiveness of body-worn technologies which have been previously discussed and may also apply to hair interfaces. These include, e.g., functional and technical considerations highlighted by Zeagler et al. [46], and social and cultural implications noted by Kao [11] such as placement on the body, communicative reach, and encompassing of ethnicity. In the following, we focus on design implications specific or particularly important for hair interfaces.



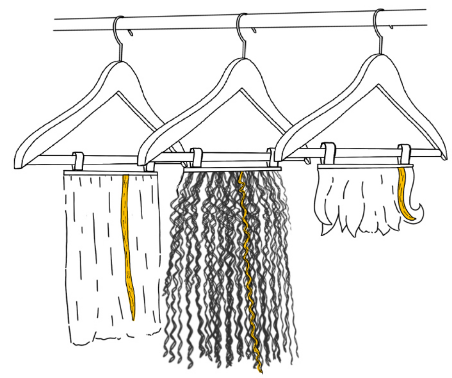
Wearability

It is desirable that an hair interface naturally blends in with the wearer's hair. However, **naturalness** comes at the cost of a decreased **discoverability**: if the interface's tactile qualities are close to human hair, it is difficult for the the wearer to locate it. Thus, sensorized hair needs to be complemented by haptic landmarks to provide orientation and guidance. Furthermore, our analysis indicates that the interface's **reachability** is crucial for physical comfort while interacting. For hair interfaces, this consideration asks for a placement close to the crown or even framing the user's face. Finally, due to the hair's flexibility and its exposed position, **malleability** of both, form factor and appearance must allow the user to adopt the wearable to their varying needs.



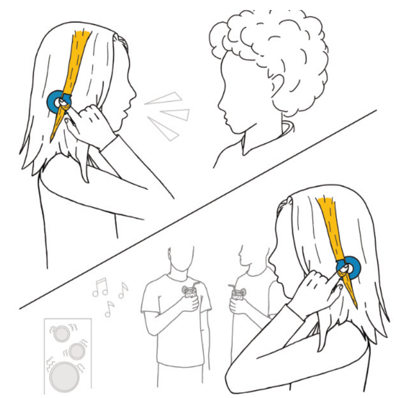
Suitable Gestures

Hair interfaces allow to explore the unique physical affordances of hair. These reveal a rich and underexplored design space for gestures that exceed planar touch gestures. Our findings encourage to incorporate fluent hair-based movement patterns that also occur naturally into the gestural design space as these exhibit a low **cognitive load** and are perceived as **unobtrusive** and **intuitive**. However, natural gestures are also prone to false activations on the technical side as well as human misinterpretation. Both needs to be considered and anticipated during interface design. Whilst capacitive touch sensing appears ineligible as stand-alone technology, we contribute first pointers that force-sensitive or hybrid sensing is a promising direction that adds **robustness**.



Diverse Users

Hair interfaces should work for diverse users. Our findings illustrates that this not only requires designers to consider gender, but also to integrate diverse facets of **identity** in the design process. Choice of material, attachment method, form factor and appearance depends on **personal preferences** that go beyond gender identity and may include, e.g., technology affinity. Due to the hair's exposed position, **aesthetics** including both device design, as well as aesthetics of interaction [19] are crucial. Considering aesthetics (e.g., fashionability) can even boost the unobtrusiveness of the interface. Furthermore, as hair is extremely versatile, some gestures and form factors **generalize** only to some types of hair. Thus, we advice against hair interfaces as one-type-fits-all devices.



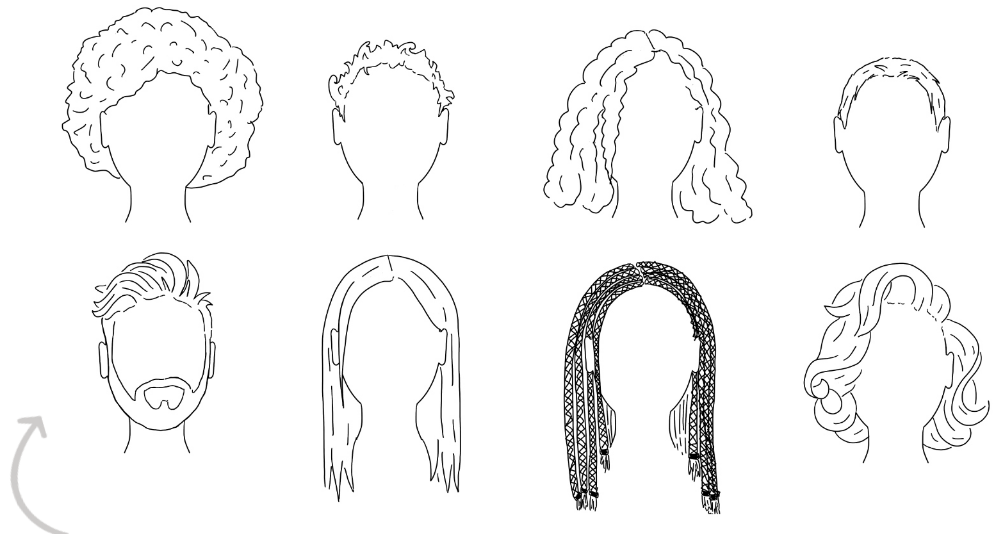
Social Context

Hair-based interactions can be very natural which allows for **hidden interactions**. Simultaneously, hair, being public, also enables a design that encourages **collaboration** and **interpersonal touch**. Yet, interactions with hair are prone to misunderstandings. The perceived appropriateness of interacting with hair is **context-sensitive**: our analysis indicates that using a hair interface is perceived as appropriate when the user is not the focus of attention, but less acceptable when they are involved in interpersonal conversations as interacting with hair may signal absent-mindedness. Thus, hair interfaces should not be designed as general purpose devices. Instead, our findings encourage designing for one primary social context in which the interface shall be deployed.

LIMITATIONS AND FUTURE DIRECTIONS

Being a prototype, FeatherHair currently has several practical limitations. First, the landmarks we integrated did not provide sufficient haptic guidance. Second, our hybrid sensing approach does not sense the exact location of a touch. Spatial resolution may be extended by adding more feather sensors along the free GPIO pins of the microcontroller. Third, the replicability of the presented polymerization procedure is limited. Anecdotal evidence has shown that the electrical resistance can vary even within the same batch of polymerized feathers as they are natural products: no pair of feathers is completely identical. Further, we observed some of our polymerized feathers to de-stain lessening conductivity over time. Thus, realizing piezoresistive sensing through polymerization of natural feathers might not be suitable for prolonged use. Briot recently presented a pre-treatment which allows to polymerize even human hair [5]. Leveraging her approach, we envision to design a hair interface which consists of real, sensorized human hair. Piezoresistivity, which requires deformation, may be explored by looking into different braiding techniques or curly hair.

As the design of FeatherHair was primarily tailored towards long, straight head hair worn down and set up in a Western style, the chosen design applies only to a subset of hair styles, cuts, and structures. Hence, future research might discuss the design of hair interfaces and hair-based interactions for a diversity of hair types to enable a more holistic view of the potential of hair interfaces as on-body technology. Additionally, since FeatherHair was evaluated with participants who grew up in Central Europe only, the generalizability of our findings is limited. Future directions of research should shed light on the role of culture in the perception of hair interfaces and hair-based interactions. This might involve cross-cultural field studies, focus groups, or expert interviews (e.g., hair stylists). We envision that this knowledge can be leveraged for the design of hair interfaces which are perceived both socially and culturally acceptable by their users.



"Hair is hair is hair? Not exactly. It is also a powerful symbol of the self."

Anthony Synnott, 1987 [36]

CONCLUSION

Until now, hair interfaces have lacked robustness, which has prevented researchers and designers from exploring them in the field and from investigating proposed interactions in a socially situated context. In this pictorial, we presented FeatherHair, a gesture-controlled hair interface that overcomes this limitation as it is robust enough to be deployed in a field experiment. FeatherHair combines the unique haptic affordances of (rooster) feathers with hybrid touch sensing realized through polymerization of off-the-shelf feather hair extensions. Our field study's results show that hair interfaces open up opportunities for novel interactions that exceed those of planar touch screens but also exhibits a strong context-sensitivity. We further present design implications which embed our work into a body of literature that contributes to the overall objective of making wearables less disruptive and more accounting for (bodily) diversity, interpersonal interactions as well as cultural and social influences.

STUDY ETHICS

We obtained ethics approval from the Ethical Review Board of the Department of Computer Sciences at Saarland University under the application numbers 21-08-7 (data collection study) and 22-01-1 (field experiment).

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REFERENCES

[1] Ahlström, D., Hasan, K., and Irani, P. Are You Comfortable Doing That? Acceptance Studies of Around-Device Gestures in and for Public Settings. In *Proceedings of the 16th International Conference on Human-Computer Interaction with Mobile Devices and Services* (2014), MobileHCI '14, Association for Computing Machinery, pp. 193–202. https://doi.org/10.1145/2628363.2628381

[2] Boldu, R., Jain, S., Forero Cortes, J. P., Zhang, H., and Nanayakkara, S. M-Hair: Creating Novel Tactile Feedback by Augmenting the Body Hair to Respond to Magnetic Field. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (2019), UIST '19, Association for Computing Machinery, pp. 323–328. https://doi.org/10.1145/3332165.3347955

[3] Boldu, R., Wijewardena, M., Zhang, H., and Nanayakkara, S. MAGHair: A Wearable System to Create Unique Tactile Feedback by Stimulating Only the Body Hair. In *Proceedings of the 22nd International Conference on Human-Computer Interaction With Mobile Devices and Services* (2020), MobileHCI '20, Association for Computing Machinery, pp. 1–10. https://doi.org/10.1145/3379503.3403545

[4] Braun, V., and Clarke, V. Using Thematic Analysis in Psychology. *Qualitative Research in Psychology 3* (2006), 77–101. http://doi.org/10.1191/1478088706qp063oa

[5] Briot, A. Stymphalian Birds: Sensing Beyond the Human Body with Feathers. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (2021), CHI EA '21, Association for Computing Machinery, pp. 1–5. https://doi.org/10.1145/3411763.3451568

[6] Briot, A., Honnet, C., and Strohmeier, P. Stymphalian Birds - Exploring the Aesthetics of a Hybrid Textile. In *Companion Publication of the 2020 ACM Designing Interactive Systems Conference* (2020), DIS' 20 Companion, Association for Computing Machinery, pp. 437–440. https://doi.org/10.1145/3393914.3395840

[7] Dierk, C., Sterman, S., Nicholas, M. J. P., and Paulos, E. HäirIÖ: Human Hair as Interactive Material. In *Proceedings of the 12th International Conference on Tangible, Embedded, and Embodied Interaction* (2018), TEI '18, Association for Computing Machinery, pp. 148–157. https://doi.org/10.1145/3173225.3173232

[8] Grosse-Puppendahl, T., Holz, C., Cohn, G., Wimmer, R., Bechtold, O., Hodges, S., Reynolds, M. S., and Smith, J. R. Finding Common Ground: A Survey of Capacitive Sensing in Human-Computer Interaction. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (2017), CHI '17, Association for Computing Machinery, pp. 3293–3315. https://doi.org/10.1145/3025453.3025808

[9] Honnet, C., Perner-Wilson, H., Teyssier, M., Fruchard, B., Steimle, J., Baptista, A. C., and Strohmeier, P. PolySense: Augmenting Textiles With Electrical Functionality Using In-Situ Polymerization. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (2020), CHI '20, Association for Computing Machinery, pp. 1–13. https://doi.org/10.1145/3313831.3376841

[10] Huang, K., Sun, R., Zhang, X., Islam Molla, M. T., Dunne, M., Guimbretiere, F., and Kao, H.-L. C. WovenProbe: Probing Possibilities for Weaving Fully-Integrated On-Skin Systems Deployable in the Field. In *Designing Interactive Systems Conference 2021* (2021), DIS '21, Association for Computing Machinery, pp. 1143–1158. https://doi.org/10.1145/3461778.3462105

[11] Kao, H.-L. C. Hybrid Body Craft: Toward Culturally and Socially Inclusive Design for On-Skin Interfaces. *IEEE Pervasive Computing 20*, 3 (2021), 41–50. https://doi.org/10.1145/3064857.3079167

[12] Kao, H.-L. C., Dementyev, A., Paradiso, J. A., and Schmandt, C. NailO: Fingernails as an Input Surface. In *Proceedings of the 2015 CHI Conference on Human Factors in Computing Systems* (2015), CHI '15, Association for Computing Machinery, pp. 3015–3018. https://doi.org/10.1145/2702123.2702572

[13] Kao, H.-L. C., Holz, C., Roseway, A., Calvo, A., and Schmandt, C. Duoskin: Rapidly Prototyping On-skin User Interfaces Using Skin-friendly Materials. In *ACM International Symposium on Wearable Computers* (2016), ISWC '16, Association for Computing Machinery, p. 16–23. https://doi.org/10.1145/2971763.2971777

[14] Kao, H.-L. C., Mohan, M., Schmandt, C., Paradiso, J. A., and Vega, K. ChromoSkin: Towards Interactive Cosmetics Using Thermochromic Pigments. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (2016), CHI EA '16, Association for Computing Machinery, pp. 3703–3706. https://doi.org/10.1145/2851581.2890270

[15] Khan, A., Roo, J. S., Kraus, T., and Steimle, J. Soft Inkjet Circuits: Rapid Multi-Material Fabrication of Soft Circuits Using a Commodity Inkjet Printer. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New York,

NY, USA, 2019), UIST '19, Association for Computing Machinery, pp. 341–354. https://doi.org/10.1145/3332165.3347892

[16] Koelle, M., Ananthanarayan, S., and Boll, S. Social Acceptability in HCI: A Survey of Methods, Measures, and Design Strategies. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (2020), CHI '20, Association for Computing Machinery, pp. 1–19. https://doi.org/10.1145/3313831.3376162

[17] Ku, P.-S., Shao, Q., Wu, T.-Y., Gong, J., Zhu, Z., Zhou, X., and Yang, X.-D. ThreadSense: Locating Touch on an Extremely Thin Interactive Thread. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (2020), CHI '20, Association for Computing Machinery, pp. 1–12. https://doi.org/10.1145/3313831.3376779

[18] Lee, D., Lee, S., and Oakley, I. Nailz: Sensing Hand Input With Touch Sensitive Nails. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (2020), CHI '20, Association for Computing Machinery, pp. 1–13. https://doi.org/10.1145/3313831.3376778

[19] Lenz, E., Diefenbach, S., and Hassenzahl, M. Aesthetics of Interaction: A Literature Synthesis. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational* (2014), pp. 628–637. https://doi.org/10.1145/2639189.2639198

[20] Li, B., Zheng, D., Lu, Y., Ying, F., and Yao, C. LightingHair Slice: Situated Personal Wearable Fashion Interaction System. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (2017), CHI EA '17, Association for Computing Machinery, pp. 1824–1828. https://doi.org/10.1145/3027063.3053093

[21] Lo, J., Lee, D. J. L., Wong, N., Bui, D., and Paulos, E. Skintillates: Designing and Creating Epidermal Interactions. In *ACM Conference on Designing Interactive Systems* (New York, NY, USA, 2016), DIS '16, Association for Computing Machinery, p. 853–864. https://doi.org/10.1145/2901790.2901885

[22] Lucero, A., and Vetek, A. NotifEye: Using Interactive Glasses to Deal With Notifications While Walking in Public. In *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology* (2014), ACE '14, Association for Computing Machinery, pp. 1–10. https://doi.org/10.1145/2663806.2663824

[23] Mayring, P. Qualitative Content Analysis. https://www.qualitative-research.net/index.php/fqs/article/view/1089/2385, 2000. Retrieved April 20, 2022.

[24] Mueller, F. F., Lopes, P., Strohmeier, P., Ju, W., Seim, C., Weigel, M., Nanayakkara, S., Obrist, M., Li, Z., Delfa, J., Nishida, J., Gerber, E. M., Svanaes, D., Grudin, J., Greuter, S., Kunze, K., Erickson, T., Greenspan, S., Inami, M., Marshall, J., Reiterer, H., Wolf, K., Meyer, J., Schiphorst, T., Wang, D., and Maes, P. Next Steps for Human-Computer Integration. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (2020), CHI '20, Association for Computing Machinery, pp. 1–15. https://doi.org/10.1145/3313831.3376242

[25] Nakamaru, S., Nakayama, R., Niiyama, R., and Kakehi, Y. Foamsense: Design of Three Dimensional Soft Sensors With Porous Materials. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (2017), UIST '17, Association for Computing Machinery, p. 437–447. https://doi.org/10.1145/3126594.3126666

[26] Pateman, M., Harrison, D., Marshall, P., and Cecchinato, M. E. The Role of Aesthetics and Design: Wearables in Situ. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (2018), CHI EA '18, Association for Computing Machinery, pp. 1–6. https://doi.org/10.1145/3170427.3188556

[27] Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., and Duchesnay, E. Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research 12* (2011), 2825–2830. https://doi.org/10.5555/1953048.2078195

[28] Rico, J., and Brewster, S. Usable Gestures for Mobile Interfaces: Evaluating Social Acceptability. In *Proceedings of the 2010 CHI Conference on Human Factors in Computing Systems* (2010), CHI '10, Association for Computing Machinery, pp. 887–896. https://doi.org/10.1145/1753326.1753458

[29] Scherz, P., and Monk, S. *Practical Electronics for Inventors*. McGraw-Hill Education, 2016.

[30] Sherrow, V. *Encyclopedia of Hair: A Cultural History*. Greenwood Press, 2006.

[31] Sonneborn, L. *Nonverbal Communication: The Art of Body Language*. The Rosen Publishing Group, 2011.

[32] Spiel, K. The Bodies of TEI – Investigating Norms and Assumptions in the Design of Embodied Interaction. In *Proceedings of the 15th International Con-*

ference on Tangible, Embedded, and Embodied Interaction (2021), TEI '21, Association for Computing Machinery, pp. 1–19. https://doi.org/10.1145/3430524.3440651

[33] Strohmeier, P., Knibbe, J., Boring, S., and Hornbæk, K. ZPatch: Hybrid Resistive/Capacitive ETextile Input. In *Proceedings of the 12th International Conference on Tangible, Embedded, and Embodied Interaction* (2018), TEI '18, Association for Computing Machinery, pp. 188–198. https://doi.org/10.1145/3173225.3173242

[34] Strohmeier, P., Pourjafarian, N., Koelle, M., Honnet, C., Fruchard, B., and Steimle, J. Sketching On-Body Interactions Using Piezo-Resistive Kinesiology Tape. In *Proceedings of the Augmented Humans International Conference* (2020), AHs '20, Association for Computing Machinery, pp. 1–7. https://doi.org/10.1145/3384657.3384774

[35] Sun, R., Onose, R., Dunne, M., Ling, A., Denham, A., and Kao, H.-L. C. Weaving a Second Skin: Exploring Opportunities for Crafting On-Skin Interfaces Through Weaving. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (2020), DIS' 20, Association for Computing Machinery, p. 365–377. https://doi.org/10.1145/3357236.3395548

[36] Synnott, A. Shame and Glory: A Sociology of Hair. *The British Journal of Sociology 38* (1987), 381–413.

[37] The Unseen. Fire. https://seetheunseen.co.uk/conceptroom/fire, 2017. Retrieved July 07, 2021.

[38] Tobita, H., and Kuzi, T. SmartWig: Wig-Based Wearable Computing Device for Communication and Entertainment. In *Proceedings of the International Working Conference on Advanced Visual Interfaces* (2012), AVI '12, Association for Computing Machinery, pp. 299–302. https://doi.org/10.1145/2254556.2254613

[39] Uhde, A., and Hassenzahl, M. Towards a Better Understanding of Social Acceptability. In *Proceedings of the 2021 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (2021), CHI EA '21, Association for Computing Machinery, pp. 1–6. https://doi.org/10.1145/3411763.3451649

[40] Vega, K., Cunha, M., and Fuks, H. Hairware: The Conscious Use of Unconscious Auto-Contact Behaviors. In *Proceedings of the 20th International Conference on Intelligent User Interfaces* (2015), IUI '15, Association for Computing Machinery, pp. 78–86. https://doi.org/10.1145/2678025.2701404

[41] Vega, K., and Fuks, H. Beauty Tech Nails: Interactive Technology at Your Fingertips. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (2014), TEI '14, Association for Computing Machinery, pp. 61–64. https://doi.org/10.1145/2540930.2540961

[42] Weigel, M., Lu, T., Bailly, G., Oulasvirta, A., Majidi, C., and Steimle, J. Iskin: Flexible, stretchable and visually customizable on-body touch sensors for mobile computing. In *SIGCHI Conference on Human Factors in Computing Systems* (2015), CHI'15, Association for Computing Machinery, p. 2991–3000. https://doi.org/10.1145/2702123.2702391

[43] Weigel, M., Nittala, A. S., Olwal, A., and Steimle, J. SkinMarks: Enabling Interactions on Body Landmarks Using Conformal Skin Electronics. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (2017), CHI '17, Association for Computing Machinery, pp. 3095–3105. https://doi.org/10.1145/3025453.3025704

[44] Williamson, J. R., Brewster, S., and Vennelakanti, R. Mo!Games: Evaluating Mobile Gestures in the Wild. In *Proceedings of the 15th ACM on International Conference on Multimodal Interaction* (2013), ICMI '13, Association for Computing Machinery, pp. 173–180. https://doi.org/10.1145/2522848.2522874

[45] Yuan, S., Ye, Q., Stenger, B., Jain, S., and Kim, T.-K. BigHand2.2M Benchmark: Hand Pose Dataset and State of the Art Analysis. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (2017), CVPR '17, IEEE, pp. 2605–2613. https://doi.org/10.48550/arXiv.1704.02612

[46] Zeagler, C. Where to Wear It: Functional, Technical, and Social Considerations in On-Body Location for Wearable Technology. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (2017), ISWC '17, Association for Computing Machinery, pp. 150–157. https://doi.org/10.1145/3123021.3123042