Eslucent: An Eyelid Interface for Detecting Eye Blinking

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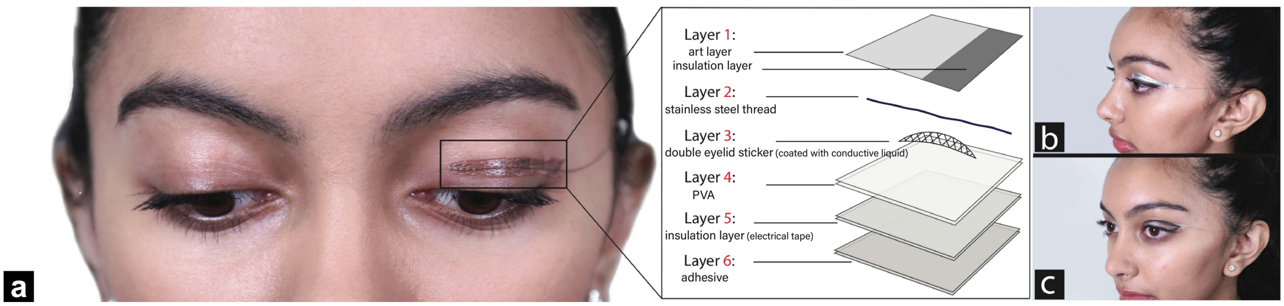

Figure 1: Eslucent is an eyelid on-skin interface for tracking eye-blinking. (a) The on-skin interface consists of 6 layers. Each layer is shown individually, layered on top of each other. The color of Esculent can be customized, for example, with (b) silver and (c) black eyeliner.

ABSTRACT

Eyelid stickers are thin strips that temporarily create a crease when attached to the eyelid. The direct contact with the crease that increases and decreases the pressure on the eyelid sticker provides a novel opportunity for sensing blinking. We present *Eslucent*, an on-skin wearable capacitive sensing device that affords blink detection, building on the form factor of eyelid stickers. It consists of an art layer, conductive thread, fiber eyelid stickers, coated with conductive liquid, and applied the device onto the eyelid crease with adhesive temporary tattoo paper. Eslucent detects blinks during intentional blinking and four involuntary activities by a falling edge detection algorithm in a user study of 14 participants. The average precision was 82% and recall was 70% while achieving the precision and recall of more than 90% in intentional blinking. By embedding interactive technology into a daily beauty product, *Eslucent* explores a novel wearable form factor for blink detection.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

On-skin interface; wearable computing; blink detection; fabrication.

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1 INTRODUCTION

Beauty products are commonly used in daily life to alter and enhance visual appearance. Moreover, they provide novel interaction possibilities due to their proximity to the skin, daily use, and acceptance, possibility to embed electronics, and to create unnoticeable wearable devices that not only camouflage the electronics within cosmetics, but also conceal interactions by using normal human behaviors as activators such as blinking [33]. We propose a seamless interface for blink detection that is directly attached to the skin, themed *Eslucent.* Eslucent interactive eyelid stickers are placed on the eyelid crease. When eyes open, the two sides of the eyelid touch which simulates a capacitive touch sensor that can be used to record blinking or other eye activities.

Eye movements disclose vital information about our psychological state. They are indicators of attention focus, visual interest, to cognitive activities. Studies show that blink frequency correlates with success in task performance (i.e., aircraft piloting) [35], as well as attentiveness during a task (e.g., reading) [35]. Eye blinking events have been used to identify a person's cognitive activity and mental state. However, existing detection methods involve the use of devices that remain visible for observers: remote camera systems [11], image processing setups [19], or infrared proximity sensors mounted on smart glasses like Google Glass [4]. These approaches are limited in portability since they require a specific setup in the space and in wearability when they require an external accessory for its use such as a hat, helmet, or glasses.

The form factor of *Eslucent* takes inspiration from eyelid stickers [6], which are thin strips for creating a temporary fold or crease on the eyelid to create the effect of an enlarged eye. Originating in Asia, it is now widely retailed and adopted across the world as a beauty product.

The design rationale for exploring eyelid stickers as a novel form factor for blink detection include: (a) eyelid stickers are a commercially available, and socially and culturally adopted beauty product [6]; (b) the direct contact and the proximity to the eye crease makes it ideal for sensing blinking through integrated capacitive sensors. The application of eyelid stickers creates a fold on the eyelid that could make the capacitive sensor to increase its values when the eye is opened (more pressure to sensor), and decrease when the eye is closed (less pressure to sensor); (c) the lightweight form and shape enables easy embedding of conductive materials; (d) easy customization to different skin tones, eye shadow colors, and eyelid shapes. As a beauty product worn daily by the authors of this paper, we are motivated to extend the function of eyelid stickers beyond a cultural body decoration, and into a wearable device for human-computer interaction. We build upon recent research in rapid-fabrication techniques for slim, conformable on-skin interfaces [10, 15, 17, 18, 22, 36–38], coupled with existing beauty practice form factors for the fabrication of an on-skin eyelid interface. In this paper, we contribute a seamless on-skin interface directly applied to the eyelid for continuous blink detection, and an exploratory 14-person user study to elicit initial reactions.

2 RELATED WORK

Wearable Form Factors for Blink Detection and On-Skin Interactions. Ubiquitous computing systems for blink detection come in the form factor of smart glasses [2, 4, 5, 13], to the use of external cameras which record eye activity for image processing [3, 9, 19], and electrooculographic (EOG) systems [1, 25]. Eslucent builds on this rich work to investigate opportunities for an alternative, on-skin interface form factor for the eyelid. Further, prior work with Head-Mounted Displays has also shown that on-skin interactions for the face can be used as an input for wearable devices [20, 27, 39]. We enable a small subset of on-skin interactions by designing a novel interface worn on the surface of the eyelid.

On-Skin Interfaces. The wearable and HCI communities have developed inexpensive fabrication approaches, generating on-skin interfaces for sensing touch input [17, 22, 24, 36, 37], displaying output [17, 34, 37], providing haptic feedback [12, 38], and texture-change output [14]. Other works have sought to create fully integrated systems that sit on the skin [15, 23]. *Eslucent* builds on prior work in on-skin touch input and extends it for an under-explored body location, the eyelid, as a station for on-skin interaction.

Eyelid-based Beauty Technology. Beauty Technology [33] integrates technology into beauty products applied directly onto one's skin [10, 18, 29, 32], fingernails[8, 16, 31], and hair [7, 30]. Specifically relevant to Eslucent are eyelid-based Beauty Technology: Blinkliflier (conductive eyelashes and eyeliner to detect blinking) [10], Winkymote (special effects makeup that detects facial movements) [29], and Chromoskin (color-changing eyeshadow tattoo) [18]. As input devices, Blinklifier and Winkymote used switches as a trigger on voluntary blinking. As an output device, Chromoskin is an interactive display on the eyelid. Eslucent extends prior input devices on the eyelid by using eyelid stickers as a novel factor of beauty technology, enabling them as capacitive sensors for more fine grained blink detection due to the capacitive sensor changes by the pressure of the crease. Eslucent considers both, intentional and involuntary blinking, and color customization to follow user's preferences (Blinklifier and Winkymote presented applications for intentional blinking, and only afford black or skin tone).

3 SYSTEM DESIGN

The system consists of three components (Figure 2): (a) the eyelid on-skin interface, which is connected to (b) the miniaturised hardware circuit board, which wirelessly transmits data to a computer for (c) blink detection and tracking.

3.1 Eslucent On-skin Interface

The Eslucent eyelid on-skin interface comprises of 6 layers (Figure 1). Eslucent detects eye blinks based on capacitance changes from eyelid movement, i.e., opening or closing eyes. The ***3-step fabrication process*** includes:

1. Sketching: Paper stencils are placed on the wearer's natural eyelid crease to measure device dimensions and shapes for custom-fit, and then digitized in design software (e.g., Paint).

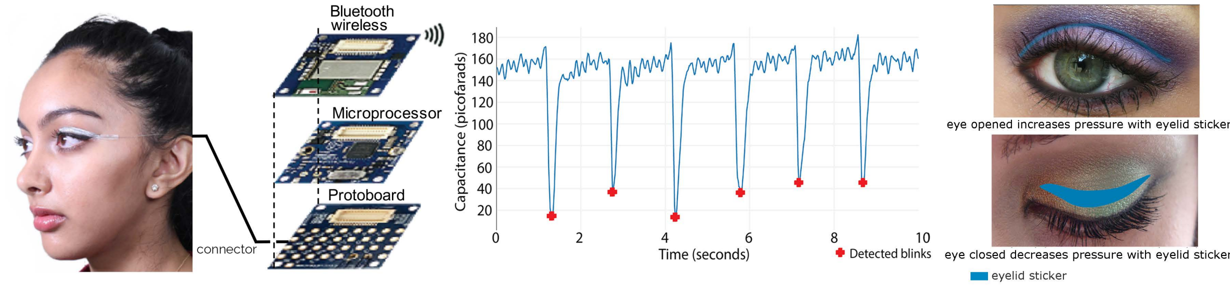
2. Fabrication

2.1. Coat Eyelid Sticker with Conductive Liquid. We coat stickers evenly with a brush by applying skin-safe liquid conductor PEDOT: PSS (Sigma-Aldrich). (Figure 1, Layer 3).

2.2. Sew conductive thread onto coated eyelid sticker. Using a commercialized sewing machine (Singer Heavy Duty Sewing Machine), we sew a conductive thread (Adafruit Stainless Medium Conductive Thread 3 ply) onto the eyelid sticker. The conductive thread serves as the connector of the on-skin interface to hardware units. (Figure 1, Layer 2 & 3)

2.3. Insulation Layer. A layer of polyvinyl alcohol (PVA) (Sulky Solvy Water Soluble Stabilizer) and transparent electrical tape (3M Translucent Polyester Electrical Tape) is applied underneath the eyelid sticker (Figure 1, Layers 4 and 5). An adhesive layer from temporary tattoos (Silhouette Temporary Tattoo Paper) (Figure 1, Layer 6) supports skin adhesion. An optional art layer (Layer 1), printed one temporary tattoo paper, can be applied for aesthetic customization.

3. Applying on skin: Place and adhere the device on the lower portion of eyelid crease with eyes closed. Make sure the wearer is comfortable when the eyes are open or blinking.



(a) On-skin interface (b) Hardware stack (c) A sample of raw data from Eslucent for blink detection. The red plus sign indicates when the algorithm detected blinks. (d) Esculent application on crease: capacitive sensor values decreases when eye is closed, and increases when eye is opened.

Figure 2: Eslucent's system overview.

3.2 Hardware

A TinyDuino microprocessor and Bluetooth module [28] wirelessly transmit capacitance data from the sensor to the computer (Figure 2 (b)). Upon receiving data on the computer, our software assigns timestamps to each capacitance value for data analysis.

3.3 Blink Detection and Tracking

The system tracks the user's eyelid movements by monitoring changes in sensor capacitance values. When the eyes are open, the electrodes come in contact with the inner skin of the eyelid crease, increasing capacitance. When the eyes are closed, the electrodes are no longer in contact with the creased skin, and the capacitance drops. Consequently, a blink results in a deep valley pattern in which capacitance values drop and then immediately increase within hundreds of milliseconds (see Figure 2c). Our algorithm is developed based on a modified falling-edge detection algorithm for detecting this pattern. The blink detection pipeline consists of the following steps: .

(1) *Smoothing.* Smooth the raw sensor values by the Savitzky-Golay filter [26] with parameters *window_length*=7 (window size, equivalent to 200 msecs) and *polyorder*=3 (order of the polynomial used to fit samples).

(2) *Calibration.* Even with the same user under a controlled setup, the mean capacitance values can change over time, prohibiting a simple threshold-based detection. To adapt to the drift over time, this step aims to find the lower bound of the sensing value change that can be considered as a blink event. We look back from a window of 45 seconds, extract the standard deviation **S** and the vertical distance **D** (i.e., difference between local maximum and local minimum). We set the lower bound **L**= **S**+**D**/**2**.

(3) *Detection.* We set the detection window to 600 milliseconds long (or 35 samples) so that it is wide enough to include a complete blink pattern. Our algorithm claims an event when the following conditions are satisfied: a) The local minimum occurs at the center of the window; b)The difference between the mean of the first quarter window and the local minimum is larger than **L**.

4 EXPLORATORY USER STUDY

We conducted an exploratory user study with 14 participants (8 Female), ages 18-40 (M=23) to elicit initial reaction towards the device. Participants wore the device and were asked to perform a different set of activities while monitoring their blinking. After collecting their input data, we ran our blink detection algorithm. This study has been approved by the Institutional Review Board of Cornell University (IRB No.:*1907008931*).

The study starts with a pre-survey questionnaire asking the participant whether they have gone through any recent eye surgery or have any eye sensitivities. If none, we proceed to collect their blinking data. The data collection procedure consists of 3 phases:

(1) Wearing Eslucent: The researcher customizes an Eslucent and places it onto the participant's eyelid crease. The researcher tests that the connection is stable, and the computer is reading data from the sensor.

(2) Performing task and data collection: The participant is asked to perform five different activities: 1) Intentional blinking: to blink in time with a metronome; 2) Talking: to have a conversation with the researcher; 3) Watching a video; 4) Solving a math problem: to solve a math algebra equation on a whiteboard; and 5) Listening to a soundtrack.

(3) Post-study interview and questionnaire: We conduct a semi-structured interview and deploy a Likert scale questionnaire, which probes user reactions towards durability, comfort, and perception.

For ground truth, we video record participant's blinking status during the entire experiment. We manually timestamped blinks based on video frames where the user's eyes are closed. For running the algorithm, we consider a blink event is correctly detected if our statistical analysis matches a ground truth blink to a detected blink within a 1-second window, allowing for 500 milliseconds of error in either direction.

4.1 Results

Blink Detection. We evaluated the result by using precision and recall as our primary evaluation metrics. We do not report accuracy due to the fact that blinks happen once every couple of seconds. A biased guess (i.e., predicting blinks never happen) gives a deceptively nearly perfect accuracy.

Our blink detection algorithm achieved an average precision of 82.6% and a recall of 70.4% across all participants (Table 1). We attribute participant data with low precision to a slight detachment of the electrodes from the applied positions (P3, 64.6%), significant head movements (P5, 68.1%), or in one case where the participant rarely blinked. For instance, P12 only blinked 12 times in a 6-minute window when solving a math problem. Missing one blink in detection has a significant impact on precision (P12, 66.1%). Participant data with low recall is due to head movements while solving a math

Table 1: Blink detection results by participants (average across 5 activities for each participant.)

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Avg.
Precision (%)	89.3	85.5	64.6	96.2	68.1	91.7	81.6	84.5	93.5	78.7	82.1	66.1	83.0	90.9	**82.6**
Recall (%)	85.2	63.9	85.3	83.8	57.6	51.6	67.6	69.7	62.7	77.8	70.5	67.6	78.3	63.6	**70.4**

Table 2: Blink detection results by activities

Activity	Precision (%)	Recall (%)
Intentional blinking	93.3	90.5
Talking	87.9	53.6
Watching	75.7	75.0
Listening to music	90.9	79.7
Solving math problem	67.4	54.6
Avg.	**83.0**	**70.7**

problem (P5, 57.6%, P6, 51.6%). Activities such as talking, watching, and listening to music all achieved over 75% precision. The recall of intentional blinking achieved 90% while watching videos, and listening to music also achieved over 75% recall. Talking and solving math problems demonstrate less desirable results due to the head movements during these activities.

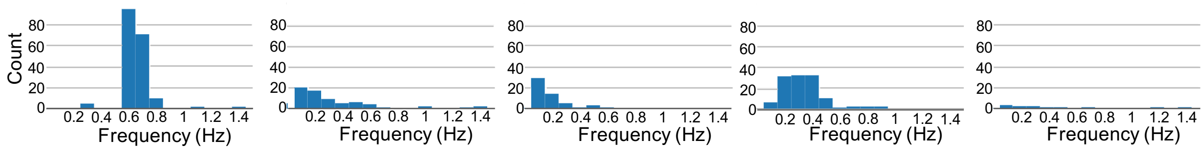
Post-Study Interview and Survey Feedback.
Mechanical durability and Comfort. Most participants reported that Eslucent remains adhered throughout the entire study (10 out of 14). Participants rated the overall comfort of the device with a median of 5 out of 7 (7=most positive, 1=most negative). Participants reported the comfort of the attachment and removal process with a median of 6. All but one of the participants reported that they become accustomed to Eslucent through the study with a median of 6.
Perception. Participants rated a median of 5 in their overall willingness to wear the device in public (7=most positive, 1=most negative). Several participants (N=7) compared it to wearing "smart contact lenses," and expressed excitement in the potential to wear it in daily life, given they could customize the aesthetics. They mentioned a broad range of preferences for device customization. Many participants (N=10, including all-male ones) preferred an invisible look, while some participants (N=3) wanted to customize it with their eye makeup, which is a feature the fabrication process supports.
Envisioned applications. Participants envisioned applications such as monitoring sleep cycle (P5, P10), drowsiness (P1, P2, P13), concentration levels (P8), exertion (P5), and interest in activities (P2, P6). Two participants envisioned that Eslucent could serve as an assistive technology to support communication (P7, P11). Others mentioned wellbeing related applications, such as a blinking reminder to avoid computer dry eye syndrome (P14) and notifying the wearer when working in a poor lighting environment (P3).

5 DISCUSSION,LIMITATIONS,FUTURE WORK

Towards Activity Recognition. Blink frequency can serve as an essential cue for activity recognition [13]. We explore the potential for blink frequency data to serve as a feature for activity recognition by analyzing the data of one participant (P13) in Figure 3. The blink frequency distribution during intentional blinking clusters between 0.6 to 0.7 Hz forms a distinct peak with up to 100 counts. For activities acquired during involuntary blinking (e.g., talking or watching a video), the centers of distributions shift to the left, indicating the blink intervals increase. For listening to music, the distribution is relatively symmetrical, with a similar number of counts in each frequency range from 0.2 to 0.4 Hz. For solving a math problem, the overall count of blinks in each frequency range is significantly less compared to other involuntary blinking activities. From the differences in blink frequency distribution for each activity, we observe the potential for it to serve as a feature for user activity recognition. In the future, by collecting more diversified data and using multi-sensor systems, such as accelerometers to sense head movements, we aim to extract additional features to classify a broader range of activities using machine learning.
Towards Personalized System. Eslucent has to be customized to individual eyelids for ideal placement. This could be enabled with a body scan and computer-aided design tools to model the on-body design of the device, which would then automatically generate optimal placement and device silhouette recommendations. Furthermore, extensive software calibration and tests should be developed to match the different eyelid types and blinking patterns.
Seamless On-Skin Interface. Advances in conductive and flexible materials such as PEDOT: PSS, eGaIn, cPDMS, and AgPDMS enable the development of on-skin interfaces [21]. Our development created a thin conductive sticker with a customized art layer that hides the sensor and replicates in shape traditional eyelid stickers to achieve stretchy moduli and conformal contact. However, advances in novel transparent, flexible, and skin-safe materials and miniaturized electronics can further streamline Eslucent into a fully integrated eyelid sticker form factor. Future projects will explore nanotechnology-based electronics on skin.
Eyelid Stickers as Design Material. Eslucent leverages the *materiality* of eyelid stickers for the design of wearable devices, building on their promising qualities of being slim, socially acceptable, and in direct contact with the skin. The inspiration for this work is motivated by the authors of this paper, who used eyelid stickers daily. Eyelid stickers, which originated as a product more commonly used for East Asians, have since been popularized and used worldwide. Moreover, we envision that, by adding an interactive component and the customization possibilities, broader audiences (especially those who may not traditionally use eyelid stickers) may now also become attracted to using these devices, which is alluded to by the positive study responses from participants of all genders.

6 CONCLUSION

We presented *Eslucent*, an on-skin eyelid interface for tracking eye blinking. We implemented the *Eslucent* system, which consists of an on-skin interface, hardware components, and a blink detection software algorithm. The system can sense both intentional and involuntary blinks. We conducted a user study to evaluate wearability. As a result, *Eslucent* achieved over 90% precision and recall when users intentionally blinked, and 82% precision and 70% in daily activities. Through integrating interactive capabilities into a daily beauty product, *Eslucent* explores a novel form factor for blink detection.



(a) Intentional blinking (b) Talking (c) Watching videos (d) Listening to music (e) Solving math problems

Figure 3: Blink frequency of P13 when performing 6 min of each activity. The horizontal axis rep-resents the frequency range with an interval of 0.1 Hz, and the vertical axis is the blink count during activities.

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