DualBlink: A Wearable Device to Continuously Detect, Track, and Actuate Blinking For Alleviating Dry Eyes and Computer Vision Syndrome

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Increased visual attention, such as during computer use leads to less blinking, which can cause dry eyes—the leading cause of computer vision syndrome. As people spend more time looking at screens on mobile and desktop devices, computer vision syndrome is becoming epidemic in today's population, leading to blurry vision, fatigue, and a reduced quality of life.

One way to alleviate dry eyes is increased blinking. In this paper, we present a series of glasses-mounted devices that track the wearer's blink rate and, upon absent blinks, trigger blinks through actuation: light flashes, physical taps, and small puffs of air near the eye. We conducted a user study to evaluate the effectiveness of our devices and found that air puff and physical tap actuations result in a 36% increase in participants' average blink rate. Air puff thereby struck the best compromise between effective blink actuations and low distraction ratings from participants. In a follow-up study, we found that high intensity, short puffs near the eye were most effective in triggering blinks while receiving only low-rated distraction and invasiveness ratings from participants. We conclude this paper with two miniaturized and self-contained DualBlink prototypes, one integrated into the frame of a pair of glasses and the other one as a clip-on for existing glasses. We believe that DualBlink can serve as an always-available and viable option to treat computer vision syndrome in the future.

CCS Concepts: • **Applied computing** → *Consumer health*; • **Human-centered computing** → Mobile devices;

Additional Key Words and Phrases: Dry eyes, Computer vision syndrome, CVS, well-being

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1 INTRODUCTION

Due to advances in computer technology more of the population finds themselves in front of TVs, computer screens, and mobile phones. Performing tasks that require visual concentration, such as looking at a screen or reading, reduces blink rates significantly [11, 35]. For example, the average blink rate drops from 15 blinks/min during a conversation to only 5 blinks/min during monitor use [35]. This is particularly alarming considering that users now look at screens longer than they sleep [30].

A reduced rate of blinking has frequently been linked to dry eyes [16, 32, 33]. The underlying cause is the evaporation of the eye's tear film, a viscous lipid layer that covers the eye. The tear film helps with vision by lubricating the eye and removing debris. Since the tear film on the eye evaporates quickly, it needs constant

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Fig. 1. Prototype with electronics integrated into the frame. This prototype is worn on the right image.

replenishing through blinking. With decreasing blink rates, the tear film thus does not fully replenish, which over time can result in dry eyes [12, 20].

A lack of blinks and thus lower overall blink rates are the leading contributor to computer vision syndrome and closely associated with dry eye syndrome [1]. Computer vision syndrome manifests itself in a multitude of symptoms, such as a headache, blurry vision, and fatigue. All these symptoms can result in problems performing everyday tasks, such as reading, driving, and computer use, which lowers the person's quality of life [27]. While computer vision syndrome has been largely overlooked [27], it is epidemic and affects up to 70% of all computer users [40].

A number of ways to alleviate dry eyes exist. Users can practice prevention habits, such as lowering the monitor, taking regular breaks, and performing eye exercises [15]. Often, however, people do not follow these practices throughout the day, as they require constant awareness. Alternatively, eye drops with artificial tears are common in helping with dry eyes. In the most severe cases of dry eyes, tear ducts can be blocked using plugs. All these treatments are suboptimal, as they can be invasive or require constant awareness.

In contrast, advances in technology can create new treatments using a feedback loop: By sensing blinks and automatically intervening when the blink rate falls below a certain threshold. For example, using a web camera as a blink detector and special screen pattern to induce blinking [6]. Existing approaches are limited to stationary computers, making them difficult to implement to continuously aid the user. To accompany the user throughout the day, sensing and intervention need to be integrated into a wearable form factor.

In this paper, we introduce a wearable approach to combating computer vision syndrome. We present and study the effectiveness of three wearable devices that track the wearer's blink rate and trigger blinks through actuation.

1.1 DualBlink: Always-available tracking and treatment for low blink rates

DualBlink is a wearable prototype device that detects blinks optically and triggers blinks with air puff actuations as shown in Figures 1 and 2. We designed DualBlink around the *duality* of behavioral treatment for dry eyes: tracking blinks and triggering blinks through actuation upon a lack of naturally-occurring blinks. We built DualBlink using the results of the two user studies we conducted to evaluate the effectiveness of a series of actuation modalities.

We believe that devices that alleviate dry eyes are more effective when constantly worn on the body. First, wearable devices can be located near the user's eyes, providing accurate sensing and effective blink triggers.

Fig. 2. Prototype that clips on the existing frame. Left image: prototype is shown next to the removable box that houses the electronics. Middle: a close-up of the IR sensor. Right: The prototype screws into the frame using an adapter on the back.

Second, wearable devices are not limited to specific settings, such as around stationary computers or laptops. This supports users even when not performing visual concentration tasks in front of desktop computers, for example when reading a book, looking through a microscope, or during the now-ubiquitous smartphone use.

In our exploration of devices, we focus on glasses; Glasses are worn by a large amount of population and their proximity to the wearer's face predestines them to comprise eye-related sensors and actuators. For the use throughout the day, a device that integrates with glasses frames must be unobtrusive, ideally small and lightweight in form factor. Furthermore, with the current trends in technology, head-mounted displays will become more prevalent and comfortable to wear [10]. Our technology could be integrated into such devices.

Since our prototype glasses are capable of tracking blinks, they can assess the *effectiveness* of their actuations and dynamically adjust actuation intensities. Such adjustments are useful in changing situations and environments, such as inside/outside, resting or in motion etc. Importantly, the tracking capability also allows our prototype devices to be virtually completely unobtrusive; if users' blink rates are high enough, no actuations will be performed by the device.

1.2 Contributions

We make the following contributions in this paper:

(1) The design and implementation of three methods to trigger blinks: light flashes, physical taps, and air puffs. All trigger modalities are integrated into tethered wearable prototypes.
(2) A controlled user study and analysis of these three trigger modalities. The results of this study indicate that air puff actuations are most effective in triggering blinks (62.4% of blinks occurred within 2 sec after the puff) while still ranked little distracting by participants (median 3 out of 10).
(3) A follow-up in-depth study to examine the effectiveness and acceptability of air puff actuations at different locations and intensities around the wearer's eye. We find that the location next to the user's eye with a high-intensity air puff (24 Volts for 75ms) yields the best blink results (60% of all triggers). We additionally evaluate the accuracy of our infrared blink detector for naturally-occurring blinks (85% accurate).
(4) Two fully integrated and miniaturized DualBlink prototypes based on the insights from our user studies. The first prototype clips onto existing glasses frames. The second is integrated into the frame itself. Both detect eye blinks with an infrared sensor, process blink rates on an embedded processor and trigger blinks with air puff actuations.

2 RELATED WORK

To the best of our knowledge, we present the first academic investigation of wearable devices to alleviate computer vision syndrome and dry eyes using behavioral responses.

2.1 Computer systems for computer vision syndrome treatment

Previous work has addressed detecting and prompting blinks from the user during computer monitor use. For example, an array of bright LEDs on the top of the monitor was used to unconsciously trigger higher blink rates [28], which showed promising results. Other projects successfully triggered higher blink rates using effects on the computer screen, such as blurring and flashing [6] or animations [29]. Both approaches detected the blink rate using a regular web camera. While both address the problem, the chosen components and setup limits their use to stationary desktop PCs or laptops. However, they do not extend to now-dominant mobile devices or no screen activities that may cause reduced blink rates, such as driving or other mobile settings more generally.

As an alternative, WinkGlasses is a commercial product that features a piece of electronically switchable fogging glass and infrared blink detection [39]. The glass becomes opaque when no blinks are detected for a period of time and clears up once blinking occurs. While this is an interesting approach, the effectiveness of the device was not evaluated. The device could also interfere with everyday activities by obstructing the view, such as during social interactions or driving where clear sight is indispensable.

A few patents [7, 19] showed passive glasses to alleviate computer vision syndrome. Glasses are coated with a material that reduces glare and reflections, thus limiting the amount of light entering the eyes. This is mainly to limit the light associated with sitting near a window or bright light source.

2.2 Blink detection

A number of related projects have incorporated blink detection into a device. Most of the work has used a camera and image processing to detect blinks (e.g., [5, 9]). Some projects have implemented blink detection for wearable setups, such as by using an infrared receiver and transmitter mounted on glasses [4]. Google Glass also used an infrared proximity sensor to detect blinks [8], but was tailored to detecting deliberate and exaggerated blinks (winks) as a gesture. Using the raw data from the same sensor, one study achieved 67% accuracy for normal blinks detection [13].

Blinks have also been detected using wearable infrared eye trackers and biopotential measurements near the eye, such as electrooculography (EOG) [2] and integrated into unobtrusive production and prescription glasses [14]. The EOG method showed to be 95.83% accurate using support vector machines (SVM) and wavelet transforms [31]. Pupil Labs created an infrared eye tracker integrated into an eyeglass frame [17].

2.3 Medical interventions that treat computer vision syndrome

Medical treatments focus on relieving dry eyes. Over the counter eye drops with artificial tears can temporarily relieve dry eyes. Prescription eye drops can be more effective and contain anti-inflammatory agents, such as steroids [15].

More invasive treatment involves putting punctal plugs into patients' eyes. Punctual plugs are made of silicone and block tear ducts to reduce tear drainage [37]. In more extreme cases, doctors can close tear ducts entirely with cauterization; a hot wire is applied to the tear duct to cause scarring, which closes the duct and prevents tear drainage.

None of these treatments provide an ideal solution. While eye drops need to be used daily, punctal plugs and cauterization are invasive and can cause inflammation and discomfort [25].

3 BACKGROUND: PHYSIOLOGICAL REFLEXES THAT CAUSE BLINKING

In our approach, we attempt to trigger *involuntary* blinks in response to a stimulus. In this section, we therefore, review existing physiological triggers that cause blinking, which has been studied extensively in the domain of medical and physiological research.

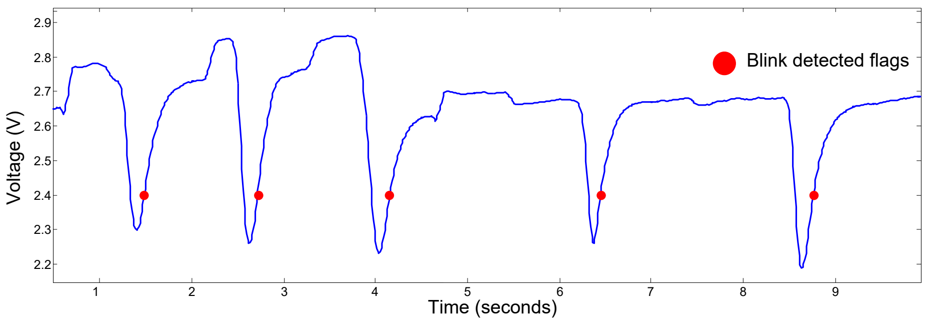

Fig. 3. A sample of raw data from the infrared sensors. The red dots indicate when the algorithm detected blinks

Corneal reflex: A protective reflex that causes blinking as a response to a mechanical stimulus of the nerves in the cornea. Air puffs to the cornea or eyelids showed to be effective blink triggers in physiological and medical research [26, 38]. Mechanical stimulation near the cornea has been shown to cause blinking, possibly from vibrations traveling to the cornea, such as tapping near the eye [21, 34]. While the tapping force was low, even such light taps on the glabella region between the user's eyes caused blinking.

Optical reflex: Protective blinking is caused by bright lights, flashes, or sudden scene changes. Previous research used $200\mu s$ light flashes to trigger blinking [34, 41]. Light stimulation proved not as effective as mechanical stimulation and became even less effective over time. Other research triggered blink responses in participants through sudden hand waving by the experimenter in front of the participant's face [24].

Acoustic startle reflex: A reflex to sudden and loud sounds (more than $115dB$) that effectively causes blinking as shown in multiple user studies [3, 34].

Electrical muscle stimulation: Although not a reflex, direct electrical stimulation of eye muscles will cause blinking. Electrical stimulation causes unilateral blinking, so electrodes on both eyes are needed [21, 34, 38].

4 DUALBLINK'S BLINK DETECTION AND TRACKING

To continuously track the wearer's blinks and monitor their blink rate, all our prototypes sense infrared reflections from the wearer's cornea or eyelid when blinking, respectively. We implemented our blink tracker using one infrared reflectance sensor (QRE1113, Fairchild) that contains both an infrared LED and a phototransistor to measure the changes in reflectance of illuminated infrared light. We leverage this setup to track blinking by analyzing infrared light reflectance as commonly done, which differs between the user's eyeball and their eyelid. Since bright infra-red light can cause irritation to the eye and heating, we kept the illumination LED brightness low at $20mW$. This intensity is within a range of the power used by most wearable eye trackers [23].

The advantage of our infrared sensor for blink tracking is its affordance of non-contact measurements. Our sensor can be easily miniaturized into the frame of the eyeglasses (e.g., as implemented by Google Glass [36]). While a pixel-based camera would provide higher-resolution data, it would also require more power and more physical space inside the prototype. We evaluate our sensor in the second study.

4.1 Processing the infrared reflections to extract blink events

We developed an algorithm for extracting blink events from the stream of infrared reflection measurements. Our primary goal was to create a lightweight and fast algorithm, such that it can run on an embedded system in real-time. Figure 3 shows the characteristic signal shape of blinks, which is present for most users while wearing any of our prototypes. A sharp downward slope appears then wearers close their eye and a rising slope for opening the eye. We use the derivatives of the signal to detect the two slopes and extract lid-down and lid-up events.

Our overall processing pipeline consists of the following steps:

(1) Infrared reflections are sampled at 30 kHz.
(2) A moving average filter of 100 values smooths high-frequency fluctuations.
(3) Data is downsampled to 100 Hz for further processing and stored into a 40-sample buffer.
(4) Calculating the derivative of the buffer then yields the characteristic downward and upward slopes.
(5) When a slope reaches a threshold, our algorithm flags blink event. Since each individual blink is different in magnitude and velocity and each user has a unique face geometry, the slope thresholds might need tuning in some cases.

5 THREE DUOBLINK ACTUATORS TO TRIGGER BLINKING

We explored the design space of physically triggering blinks. Our initial exploration was based on findings in the literature that informs our design of blink actuators as outlined in the related work section. We selected actuation modalities that meet the following design criteria: First, the actuator needs to be small enough to be worn comfortably on a pair of glasses and afford further miniaturization in the future. Second, the actuator must not cause pain or discomfort. Third, the actuator should trigger involuntary blink responses. Fourth, the actuator must not disturb surrounding users and must have the potential to eventually be socially acceptable for the wearer.

We arrived at three actuation modalities: flashing light, physical tapping, and air puffs as shown in Figures 4, 5, and 6.

5.1 Flashing a light

To trigger the user's optical reflex, we designed a first wearable prototype that mounts an RGB LED light (Adafruit Neopixel) near the eye. When activated, the LED flashes for 15 ms to produce a short but noticeable trigger. Red, green, and blue were flashed simultaneously to produce perception of white light.

Fig. 4. Glasses with an LED light flash. The whole frame is shown on the left. A close-up of the LED is shown on the right.

5.2 Physical tapping near the eye

To trigger the user's corneal reflect using physical contact near the eye, our second wearable prototype produces light taps through a small linear servomotor (Spektrum RC H20240T). We picked this actuator due to its small size, fast speed, and large linear travel distance. We attached a piano wire to transmit the force and added a round plastic tip that contacted the skin. The travel distance was controlled by the processor to accommodate different face sizes. Through each user's feedback, we manually adjusted the actuator travel distance so as to *lightly* tap the user's face.

Fig. 5. Glasses with a linear actuator for tapping. The whole frame is shown on the left. A close-up of the linear servo is shown on the right.

5.3 Puffing a jet of air near the eye

Similar to physical tapping, our third prototype triggers the corneal reflex to induce blinking. However, instead of physically *touching* the skin, it blows a short and small jet of air towards a location around the wearer's eye. An air puff is potentially more pleasant than a physical tap. At the same time, the air pump is less loud and more power efficient than a linear motor. We used a small piezoelectric microblower (MZB1001T02, Murata), which provided enough pressure to be noticed by the user. We built a nozzle to concentrate the air, which we mounted in a socket joint to afford easy adjustment of the target location of all air puffs. The target location needs adjustment to avoid blowing directly into the wearer's eye, which would be counterproductive as it may cause irritation and possibly dry the eye even more.

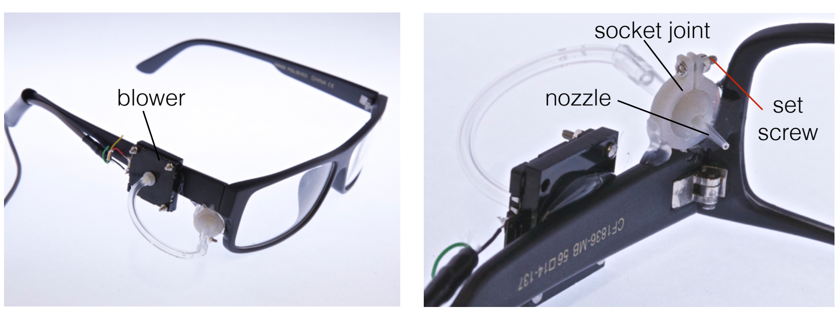

Fig. 6. Glasses with the air puff, that were used in the user study. A close up of the nozzle assembly is shown on the right.

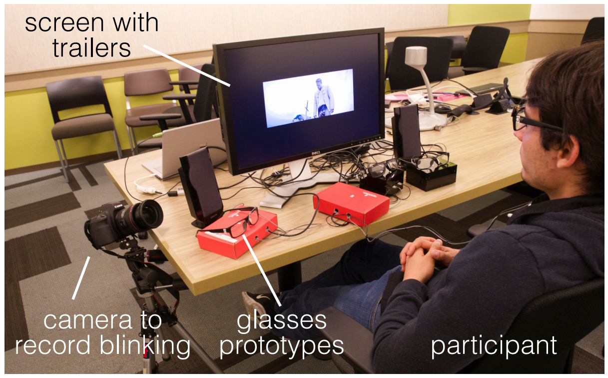

Fig. 7. The setup during the first and second setup. The participant watched trailers on the monitor while wearing each of the four prototype glasses.

5.4 Actuators that did not satisfy our requirements

In exploring the design space of potential actuators, we built a series of prototypes that could not fulfill the goals stated above. While experimenting with solenoid coils for quick tapping, we found them too bulky to be effectively mounted on a pair of glasses. We also tried out vibration motors as actuators on the glasses, but learned that the physical stimulus they produce is uncomfortable rather than effective in producing blinks. Our attempt to integrate electrical muscle stimulation into our approach revealed that the electrodes are uncomfortable during continuous wear and invasive in producing blinks directly. Finally, we attempted to produce loud sounds near the user's ear, but could not converge on a feasible approach, since the sound levels required would cause bystanders to also notice the triggers or require users to constantly wear headphones.

6 EVALUATION: EFFECTIVENESS OF ACTUATORS (FLASHING LED, PHYSICAL TAP, AIR PUFF)

The goal of this experiment was to compare the three actuators described above in a controlled lab evaluation. To compare their effectiveness with a baseline condition, we built a fourth prototype that only tracked blink events, but featured no actuation.

6.1 Task

The participants' task was to watch four minutes of new movie trailers and to answer two questions after each trailer on the contents. While watching the trailers, participants wore each of our prototype devices and were told that the goal of the evaluation is to measure the distraction of our prototypes caused to watching trailers. We did not tell participants that the goal of this study was related to tracking or triggering blinking. After each trial, participants rated how distracting the respective interface was on a Likert scale from 1 (not at all distracting) to 10 (very distracting).

We picked trailers since they are designed to capture the attention of any viewer [18]. Specifically, we chose action trailers for short sequences and frequent cuts. We had found in a previous pilot study that comedy and horror trailers can cause more emotional responses, such as laughter, which may inadvertently impact blink rates.

6.2 Actuation Interfaces and Experiment Procedure

We studied four actuation *interfaces* in this evaluation: *flash LED*, *physical tap*, *air puff*, and *no actuation*. The latter was our baseline condition that only tracked blink rates, but performed no type of actuation to trigger blinks in participants.

Each trial consisted of watching four minutes of movie trailers. The actuator on each prototype triggered at specific intervals that we hardcoded before the study, each being between 2 and 10 seconds. Each trial contained a total of 30 triggers and the order of trigger intervals was counterbalanced across trials and participants.

Each participants repeated two *blocks* of this procedure during the experiment so as to account for sequence effects of the actuation interfaces described above. Between the two blocks, participants took off the prototype devices, left the room, and walked around the building to relax their eyes. The order of actuation interfaces was counterbalanced across blocks and participants.

A high-resolution DSLR video camera recorded participants throughout the study at 60 fps to obtain ground-truth data on actuation triggers and blink events. Overall, each participant completed a total of 4 interfaces $\times 2$ blocks = 8 trials and completed the study in under an hour.

6.3 Participants

We recruited 12 participants (7 female), ages 23–55 from our institution. 9 participants did not normally wear glasses or contact lenses. 3 participants wore contact lenses during the study. All participants were heavy computer users and spent around 10 hours on a computer every day. Participants received a small gratuity for their time.

6.4 Results

To obtain accurate results, we manually labeled the timestamps of actuation and blink events in footage recorded by the DSLR camera. Watching the videos in slow motion at 0.3 speed ensured that all timestamp labels were accurate within a range of 1 sec.

We examined four metrics for all interfaces. 1) Participants' mean blink rate while wearing each of the prototypes reveals how successfully each of our actuation interfaces is capable of producing a regular blinking behavior. 2) The average actuation-blink interval indicates the effectiveness of each interface to trigger a blink. 3) Closely related, we measure the effectiveness of an interface by the rate of blinks that occurred within two seconds after an actuation (i.e., a successful actuation). We chose this time span to account for inaccuracies in labeling the raw footage. 4) The median distraction rating for each interface informs the design of future prototypes by how annoyed participants were with a particular method of actuation.

In addition to processing these metrics for our three actuation prototypes, we also processed them for our fourth prototype, which had no means of blink actuation. Similar to the other three interfaces, when wearing the *no actuation* prototype the actuation indicator flashed visibly to only the camera at controlled intervals. The purpose of this behavior was to compare the blinks resulting from our three prototypes' actuations with naturally occurring blinks.

6.4.1 Mean blink rate. We ran a two-way ANOVA with factors *interface* and *block* on mean blink rate with the participant as the random variable. We found a significant main effect of *interface* ($F_{3,8} = 6.582, p < .015$) on mean blink rate and a significant interaction between *interface* and *block* ($F_{3,8} = 5.105, p < .029$), both compared for significance at the .05 level. Post-hoc t-tests using Bonferroni correction showed a significant difference in participants' blink rates when wearing the *physical tap* prototype and the *no actuation* prototype ($p < 0.026$). As shown in Figure 8, wearing *physical tap* increased participants' blink rate by 35.8% on average.

6.4.2 Average actuation-blink interval. We ran another two-way ANOVA on the average delay between actuations and subsequent blinks and found a significant main effect of *interface* ($F_{3,8} = 5.026, p < 0.03$). Post-hoc

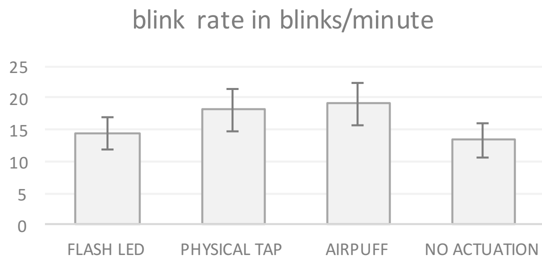

Fig. 8. Mean blink rate for each of the interfaces.

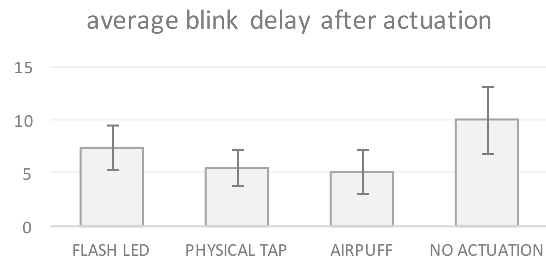

Fig. 9. Mean delay (ms) to blink after actuation. In "no actuation" case, actuation was led flashes that were only visible to the camera.

t-tests using Bonferroni correction revealed a significant 49.5% decrease of average blink delay when participants switched from *no actuation* to *air puff* as shown in Figure 9.

6.4.3 Rate of blinks occurring within the first two seconds after actuation. For this metric, a two-way ANOVA on the rate of blinks following actuations within two seconds showed a significant main effect of *interface* ($F_{3,8} = 6.609, p < .015$). Post-hoc t-tests using Bonferroni correction revealed statistically significant differences between *no actuation* and *physical tap* ($p < .006$) as well as between *no actuation* and *air puff* ($p < .014$). As shown in Figure 10, participants successfully blinked for 62.4% of all actuations within two seconds when wearing *air puff*, which is almost twice as much as when wearing *no actuation*. When wearing *physical tap*, participants on average blinked in response to 56.2% of all actuations within two seconds (80% increase) compared to *no actuation*.

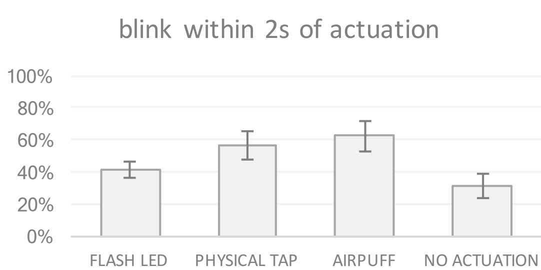

Fig. 10. Rate of successful actuations per interface.

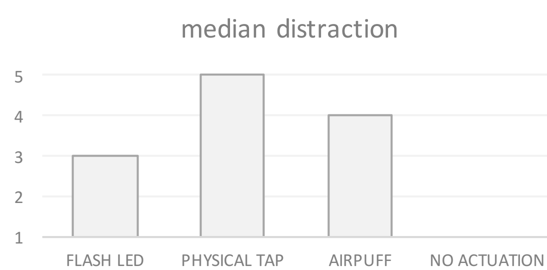

Fig. 11. Median distraction ratings for each interface.

6.4.4 Participants' median distraction rating. As shown in Figure 11, participants rated all actuation interfaces within the lower half of the one-to-ten Likert scale. While participants assigned *physical tap* a median 5 rating, *air puff* is slightly lower at 4 and *flash LED* at 3.

6.5 Discussion

The results of this evaluation show that the actuation in our prototypes impacts the blink rate, most evident by the *physical tap* interface. Though *flash LED* and *airpuff* produced no significant difference at the .05 level for blink rate, the results of *airpuff* are promising. Our second metric confirms this, showing the lowest average delay between actuation and blink for *airpuff* overall.

Contrary to what we expected, *physical tap* was not the most effective in triggering blinks. Instead, *airpuff* produced the lowest mean actuation-blink interval and highest success rate of producing blinks overall. It is possible that the effectiveness of *physical tap* decreased throughout a trial, because the actuator did not always make skin contact. Even though we adjusted the actuator before a trial to ensure it made light contact with each participant's skin based on their feedback, we noticed that some participants reported skin contact while there was none. Interestingly, we noticed that some participants blinked due to the auditory side effect of *physical tap*, most likely in anticipation of the physical impact.

The results indicate that *flash LED* was not as effective as *airpuff* and *physical tap*. *Flash LED* produced a slight increase in response compared to no actuator. To increase the response, it is likely that the LED needs to be brighter and positioned in front of the eye. In our experiment, the LED was positioned in the peripheral vision of the participant. However, even so, participants rated *flash LED* as quite distracting with a median rating of 3. Some participants were considerably sensitive to light and found the LED to be the most disturbing actuator. In a wearable setup, it is thus unlikely that the LED flash can be made noninvasive and still produce a large effect.

As expected, *physical tap* was the most distracting. *Airpuff* was in the middle and *flash LED* was the least distracting. The tapping motor produced a sound that many participants found more distracting than the actual skin contact, which might have contributed to a higher distraction rating. Although *airpuff* also produced a light sound, it was barely noticed by participants. Future versions of *physical tap* could integrate a more silent motor through insulation and custom transmission, but we have not so far been able to find suitable motors on the market.

Overall, We found that *airpuff* struck the best balance between success rates and distraction. *Flash LED* had less use overall, as it only produced a slight effect on the blink rate. *Physical tap* was similarly effective in producing blinking, but distracted participants more.

On the practical side, these results are promising for fulfilling our initial objectives. Integrating the air puff actuator into a wearable device is easier than accommodating the moving parts of the motor. In addition to this limitation, the parts of the motor are audible, less reliable, and are noticeable in social settings.

Since *airpuff* performed best all things considered, we study it in more detail in a follow-up evaluation.

7 FOLLOW-UP EVALUATION OF *AIRPUFF*: 3 LOCATIONS, 2 INTENSITIES, 2 DURATIONS

In this evaluation, we examine different actuation locations around participants' eyes and intensities and durations of air puffs to learn more about their effectiveness and participants' acceptance ratings.

7.1 Task

Participants had the same task in the previous experiment: watching movie trailers while wearing a prototype device, answering two questions on the trailer, and rating the distracting and invasiveness of each device. To accommodate more trials during this evaluation, trailers were only two minutes long.

Similar to before, we did not mention to participants that the true focus of the study is sensing each participant's blink rate and triggering blinks through actuation.

7.2 Actuation Interfaces and Experiment Procedure

In this study, participants wore the same prototype device that triggered blinks through airpuffs. We introduced three factors in this evaluation:

(1) Location. We adjusted the nozzle of the blower to one of the three locations shown in Figure 12: *ABOVE* the eye, *NEXT* to the eye, or *BELOW* the eye.

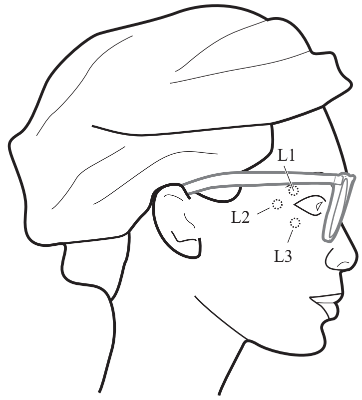

Fig. 12. Locations evaluated in the air puff study: (L1) above the eye, (L2) next to the eye, and (L3) below the eye.

(2) Intensity. The voltage applied to the piezo blower, which resulted in *STRONG* (24 V) and *WEAK* (12 V) actuations.
(3) Duration. The duration of the air puff was either *SHORT* (75 ms) or *LONG* (150 ms).

Each participant completed 3 locations ×2 intensities ×2 durations = 12 trials in total in under an hour. A DSLR camera again recorded each participant at 60 fps.

7.3 Participants

We recruited fresh 12 participants (6 female), ages 24–47 from our institution. 8 participants did not wear glasses or contact lenses. 4 participants wore contact lenses during the study. All participants were heavy computer users and spent around 10 hours on a computer every day. Participants received a small gratuity for their time.

7.4 Results

Repeating the procedure of our analysis from Study 1, we again manually labeled the timestamps of actuation and blink events in the footage recorded by the DSLR camera during the second evaluation in slow motion.

Since we knew that the *air puff* prototype can successfully trigger blinking in response to actuation, we focused this analysis on the success rate (i.e., a blink within 2s, 3^{rd} metric in Study 1) and participants' ratings on distraction and invasiveness of our prototypes. We performed the same calculations as described in the first study to analyze and compare all conditions.

7.4.1 Rate of blinks occurring within the first two seconds after actuation. We ran a three-way ANOVA with factors *puff location*, *puff intensity*, and *puff duration* on the rate of blinks following actuations within two seconds. We found significant main effect of *location* ($F_{2,4} = 7.734, p < .042$), *intensity* ($F_{1,5} = 14.116, p < 0.013$), a significant interaction between *location* and *duration* ($F_{2,4} = 8.657, p < .035$), all compared for significance at the .05 level. Post-hoc t-tests using Bonferroni correction showed a significant difference in successful actuation rates when air puffs were targeted to the location next to the eye compared to above (35.5% increase), resulting in a success rate of 60% as shown in Figure 13 (left). We also found a significant difference between weak and strong intensities. On average, strong air puffs produced blinks for 54% of all actuations as shown in Figure 13 (center), which is a significant 16% increase over weak air puffs.

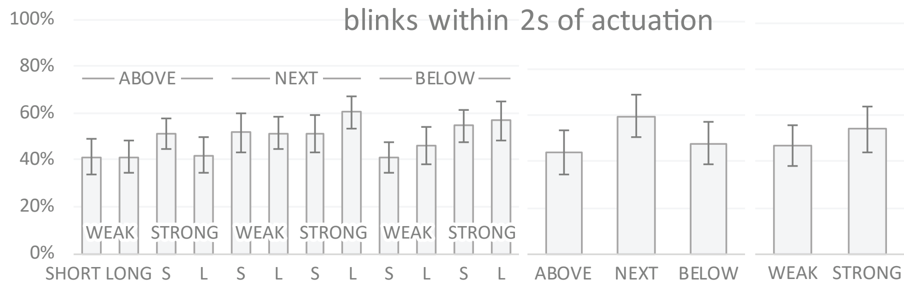

Fig. 13. Average rate of successful actuations for each combination of {location, intensity, duration}. The two charts on the right show aggregated values for the factor location and intensity, both of which showed statistically significant differences.

7.4.2 Participants' median distraction rating. As show in Figure 14, participants again rated the air puff actuations within the lower half of the one-to-ten Likert scale for all locations, intensities and durations. While the location *next* to the eye received a median rating of a full point less distractive than *below*, changes in air puff intensity and duration resulted in marginal or no changes in median ratings.

Regarding the perceived invasiveness of each of the configurations, Figure 15 shows participants' ratings. The results show that all interfaces again received comparable ratings in the 3 out of 10 region.

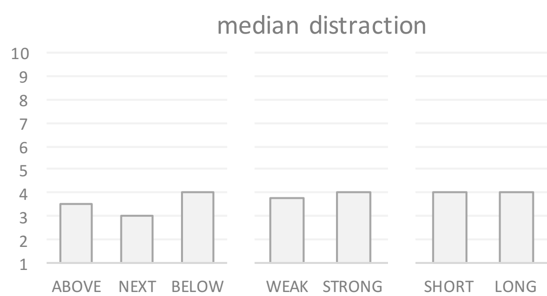

Fig. 14. Participants' median distraction ratings (1: not at all distracting, 10: very distracting) for all locations intensities and durations.

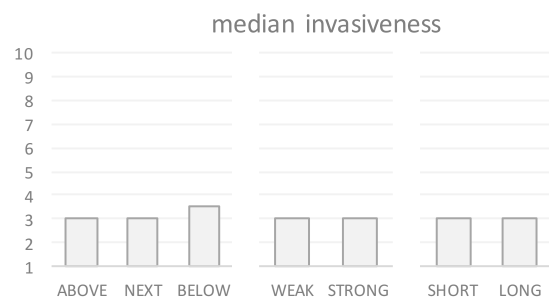

Fig. 15. Participants' median invasiveness ratings (1: not at all invasive, 10: very invasive) for all locations intensities and durations.

7.5 Accuracy of our infrared blink-detection algorithm

We reused the manually-labeled data from this evaluation to test the accuracy of our blink detector. As shown in Figure 2, the prototype participants wore during the second study also contained an infrared sensor to record eye blinks during all trials. We did not test the infrared sensors in the first study, since multiple prototype glasses had to be removed and put on many times. The position of the glasses would have to be adjusted after such events, making the study longer than planned 1-hour.

Compared to the labeled ground-truth blink events, our blink detector captured an average of 85.2% of all blinks (SD = 8.1%) across all participants. The sources of error could be facial movements such as laughter, talking and yawning can be picked up as blinking. Also, misalignment or shifting of the glasses can cause errors, as the IR sensor is sensitive to distance and alignment.

7.6 Discussion

The results of this experiment show that the location of the air puff actuation is important, as it affected the blink success rates. Location *next* to the eye was the most promising: It had the highest (60%) blink success rate and was rated 3 out of 10 on the distraction and invasiveness ratings. Other locations produced lower blink success (no statistical significance), but the location *next* to the eye makes integration easier. In this configuration, the blower can be integrated directly into the frame, with air channels routed and hidden inside.

Unsurprisingly, *high* intensity (24 V) produced more blinks compared to *low* intensity (12 V). High and low intensities were similar on the distraction and invasiveness scales, indicating that they were perceived similarly. Even though higher voltage could potentially be more effective, the pump we chose for our design does not handle more than 24 V. There was no noticeable difference between *short* and *long* air puff actuations. We thus conclude that *short* air puffs are preferred since they use less energy, which is critical for battery life of a wearable device.

To summarize, the configuration settings of air puffs that struck the best balance between least distraction, least invasiveness and highest effectiveness were: *next* to the eye, *high* intensity (24 V), and *short* duration (75 ms).

The 85.2% accuracy of our blink detector shows the viability of our approach for wearable and embedded purposes. Since even the baseline blink rate we observed in the first study varied substantially between individuals, the sensor would have to be calibrated when first worn. The sensor would then detect changes from the baseline rate, rather than the absolute blinking rate.

8 TWO FULLY INTEGRATED DUALBLINK PROTOTYPES

Based on the results of our two user studies, we designed two miniaturized and wearable prototypes, as shown in Figures 1 and 2. Our design goal was to make a small and unobtrusive wearable device, which can be either mounted onto existing glasses or directly integrated into the frame of a pair of glasses. Both prototypes have identical electronics and system architecture (Figure 17)and only differ in the attachment mechanisms.

8.1 Electronics Design

We designed a custom circuit board (Figure 16) to miniaturize and integrate all electronics. An ARM Cortex M0 (ATSAMD21G, Atmel) microcontroller is the main processor on our final device. To provide wireless connectivity to smartphones or computers, we integrated a Bluetooth Low Energy radio (NRF8001, Nordic). A 250 mAh lithium-polymer battery power the device, which ran for approximately 6 hours. The piezoelectric blower is challenging to drive since it requires high voltage (24 V) alternating current. Since this is not readily available on a battery-powered device, we use a boost switching regulator (MIC2288, Microchip) and a DC to AC converter that we designed to drive the piezoelectric blower. A 4-Mbit FRAM memory chip (CY15B104Q, Cypress) serves as storage for log data and additional off-line analysis.

8.2 Mechanical Design

We used off-the-shelf glasses as a base frame (Kayden, Newbee Fashion) and 3D printed a custom adapter for the piezoelectric pump on a Stratasys Eden260V to accommodate the silicone tube. The tube connects to a nozzle that is made from a plastic dispensing syringe. We designed a ball and socket to hold the nozzle in place, which allows the nozzle to swivel through manual adjustments and can be secured with a screw.

We designed two mechanical prototypes. One design clips on the side of the glasses using screws as shown in Figure 2 and can be attached to any glasses that users may wear already. The second prototype is integrated into the frame of the glasses as shown in Figure 1. It is smaller and arguably more aesthetic than the first prototype, but cannot be removed or attached to another frame. We believe that both prototypes have merits in real-world usage.

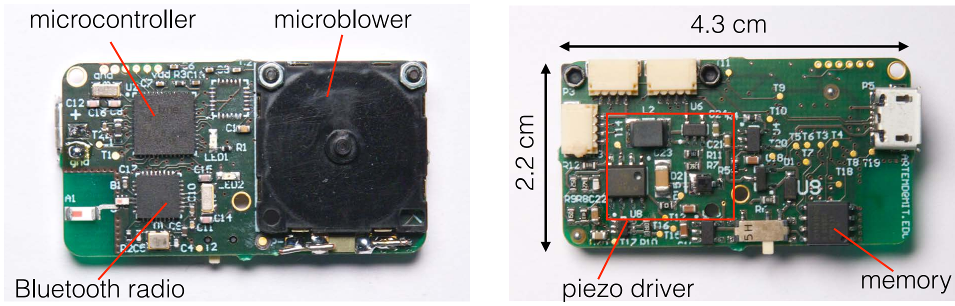

Fig. 16. Pictures of the top and the bottom of the custom circuit board.

8.3 Technical Evaluation

Power consumption is an important consideration for the external and continuous use of our prototype devices. A wearable device should last at least a few hours without a need for recharging.

For our final DualBlink prototype, the base power consumption (all at 3.3 V) is 22.8 mA. The blower consumes about 202 mA when operated continuously, but for our purposes it is active only for a fraction of a second in large intervals. The infrared illumination LED uses 16.5 mA, which is the biggest consumer of energy, since it needs to be on most of the time. In its current implementation, DualBlink affords a continuous wearable operation for 6.3 hours if the blower triggers blinks once every minute.

Future versions of DualBlink could improve the battery life by reducing the average infrared illumination power by duty cycling. For example, turning off the infrared LED right after a blink for a brief period is acceptable, since there is some minimum interval between the blinks. An iteration of our current device design may also include an additional battery alongside the other frame of the glasses, or hidden behind the wearer's ear as is the case for Google Glass or Jins Meme [22].

The total weight of the clip-on prototype is 43 grams, whereas the integrated prototype weighs 40 grams. The weight of the unmodified glasses frame is 21 grams Both weights are comfortable for everyday wear.

For in-the-wild evaluations, it will become important to store blink and actuation data whenever the prototype cannot connect to a mobile device. DualBlink can currently store data at 100 Hz for 60 minutes, which should cover the periods of time when mobile devices are not in range.

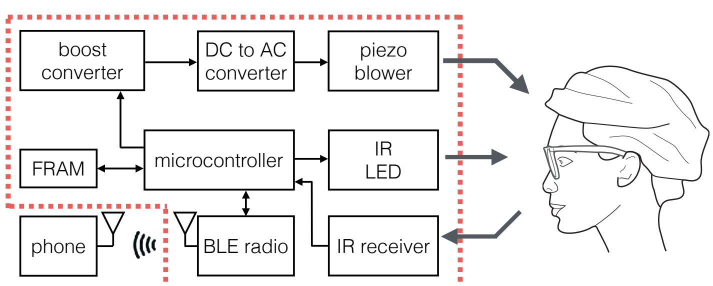

Fig. 17. System diagram. The components of the wearable system are shown in the red box.

8.4 Usage in the wild

We demonstrated and studied different components of our DualBlink prototypes in this paper: an actuator and blink detector as well as electrical and mechanical parts. In this section, we tie them all together and explain the device's use in real-life.

First, an individual with eye problems would go to the eyeglasses store. There the individual would be fitted with the special glasses frame that contains our system. This could be either built-in or attached to existing glasses. The sensors and actuator would be adjusted to suit the individual's face. This would be done to increase the accuracy of the infrared sensor and find a suitable location for the air puff. Alternatively, the fitting could be done at home. The individual would wear this frame throughout the day. At first, it will monitor the blink rate only. This will help to establish a baseline for the normal blink rate. Then the air puff will be activated when the blink rate falls below the established threshold. The device will also connect to the smartphone to store and visualize the data. This information will be useful to measure the effectiveness of the device and also to provide information for medical professionals.

9 LIMITATIONS AND FUTURE WORK

9.1 Long-term medical evaluation

Our evaluation and the results we obtain are valid for the population we recruited: frequent users of computer screens, none of who had known dry eye syndromes. To learn about the medical accuracy of our approach and determining the effectiveness of DualBlink for alleviating computer vision syndrome, we have started to prepare an in-the-wild and longer-term evaluation in collaboration with University of Washington Medicine. We are planning on running a multi-day study during which patients with diagnosed computer vision syndrome are wearing our devices throughout the day.

9.2 Infrared blink detection

Our current blink detection is sufficient for the operation of the device; at 85% accuracy, missing a blink event during detection would only cause the actuator to trigger sooner, which could be constrained with a minimum threshold value. However, to extend beyond user studies in which prototype frames can be manually fitted and adjusted to each participant to a prototype that works out-of-the-box for a much wider audience, the blink detection needs to be more robust. It should be able to accommodate different face and eye shapes as well as be tested with different skin tones. It should also work if the glasses shift on the face, for example, while walking or sudden motions. Either multiple infrared sensors may deliver a more reliable signal for such scenarios or a custom-fitted frame to accommodate the face anatomy similar to prescription glasses frames. Also, the infrared detection will need to be tested in direct sunlight, as it might influence the sensor.

9.3 Integration into exiting augmented glasses and headsets for augmented and virtual reality

Our results also inform the design of future wearable glasses that incorporate displays, which are currently emerging in the domain of AR and VR. Such devices will cause even more screen use and exposure for users, potentially increasing the severity of dry eyes and computer vision syndrome in users. In addition, more recent headsets incorporate eye tracking for foveated rendering, which could be repurposed to implement DualBlink's approach.

Since headmounted displays are close to the user's eyes, alternative approaches to our *physical* stimulation could be purely virtual inside an immersive environment. For example, virtual explosions or objects moving quickly towards the users face will cause blinks by triggering the optical reflex. Loud audio output through speakers or the headphones of the headset could supplement blink actuations by triggering the acoustic startle reflex, potentially in unison with visual stimuli.

9.4 Earpiece prototype without glasses frames

Finally, one of the current disadvantages of our design is the need to wear glasses in the first place, because not everyone may feel comfortable wearing glasses. While our current design affords integration into head-mounted devices (e.g., Google Glass, Jins Meme, Hololens etc.), an unobtrusive device might be more desirable for users. To make the device completely unobtrusive, we are experimenting with the integration of all components into a small earpiece that is worn either in or behind the outer ear. We believe that in the future, users could wear such a device that is seamlessly integrated into a small earpiece, which would allow universal wear.

We have started to test the feasibility of sensing electric muscle potential (EMG) around the ear to pick up blinks, but not achieved comparable success rates so far. Similarly, we are intrigued by our observations during the study that participants started blinking in response to the auditory activation of the *physical tap* interface even *before* the pin made contact with their skin. One avenue of future work is to determine whether the *physical tap* can provide a lasting conditioning effect, such that DualBlink may produce future actuations simply by playing back the actuators sound. We are also planning on experimenting with ultrasound transducers that produce just enough of a pressure wave to trigger the acoustic startle reflex.

10 CONCLUSION

Computer vision syndrome can significantly reduce the quality of life. As computer and screen use is increasing, this problem affects more and more of the population. In this paper, we have presented DualBlink, a miniature wearable device that can potentially alleviate computer vision syndrome and dry eyes. We base the system design on two user studies of different subsystems and variations of blink actuation. In our first evaluation, we compared three actuators to trigger blinking and evaluated the most effective one in detail during our second study.

We believe that our work provides a novel always-available way to alleviate computer vision syndrome and that our results have implications for emerging head-mounted devices and displays. Improving the quality of life for large part of the population suffering from this problem may become a result of our work. We also hope that our approach in creating always-available wearable treatments can be extended to many other health and well-being issues.

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