Understanding Privacy-friendly Design of Robot Eyes

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ABSTRACT

Eyes have been widely found to play an important role in communicating emotions and intentions for social robots. However, when introducing robots with eyes into people's personal living spaces, it is necessary to consider how the social aspects of a robot impact perceptions of privacy. Specifically, in this paper we explored how the design of a robot's eyes and eye-use behavior impacts use perception of privacy and related concerns. We developed a prototype robot with display-based eyes and investigated the impacts on perceptions of privacy concerns living with the robot. Our findings indicated that robot eye design does impact perceptions of privacy concerns, with the unexpected result of robots whose eyes that stay always on garnering lower concerns than eyes that close or turn off (the display) just before a person leaves. This result offer valuable insights for robot development and present empirical evidence on the influence of robot eye design on user privacy concerns.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**; • **Security and privacy** → *Social aspects of security and privacy*.

KEYWORDS

Human-robot interaction, Social robot, Robot eye design, privacy-sensitive design

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Figure 1: We explore how different designs of a robot's eyes influence users' privacy concerns. *Left*: Open eyes design. *Center*: Black eyes design. *Right*: Closed eyes design.

1 INTRODUCTION

The rapid development of social robots has led to their use in various areas, including medicine, education, and customer service. These robots are designed to interact with humans naturally and intuitively, and their appearance and behavior are key elements for successful human-robot interaction (HRI). However, as these robots become more integrated into our lives, privacy concerns have arisen [24]. For example, privacy-related discomfort from the intrusion of an animal-shaped robot into a living space can discourage its use [11]. In examining this issue, we focus on the robot's eyes and how a robot's eye use impacts perceptions of privacy.

The perception of being watched by a robot with "eyes" (e.g., an image of an eye [5, 13, 16] or an image of a robot with eyes [9, 29]) may induce prosocial behavior in humans. While this has potential benefits such as providing nonverbal cues [2, 28] to support effective human-robot interaction, this same prosocial reaction can intensify feelings of being under surveillance [24] and pose a threat to perceptions of privacy. Life-like robot eyes in particular can induce a sense of being watched and spied on [22], which can reduce opportunities for interiority and self-reflection [24]. Our goal is to identify an eye design that can mitigate the privacy concerns that a robot with eyes could bring. Specifically, we hypothesized that displaying eyes that imply an inactive state during non-interaction periods could reduce privacy concerns associated with living with robots. While it may be conventional to consider a state of eyes being "always on" as the default baseline, and turning them off as the primary action to provide a clear indication of the robot's inactive state, we propose the life-like solution of closing the eyes to be more natural. Our research questions (RQ) are as follows:

- **RQ1**: Does the perception of a robot's eyes being life-like correlate with privacy concerns?
- **RQ2**: Can privacy concerns be mitigated by eye expressions that imply an inactive robot state?

To answer these research questions, we created a robot prototype that is capable of a range of eye display behaviors (see Figure 1), and conducted a video-based experiment to investigate perceived

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privacy concerns relating to interactions between the robot and a person. We evaluate the impact of each robot with different eye designs on its life-likeness and users' privacy concerns with a questionnaire.

Our results indicate that, unexpectedly, robots that close or turn off their eyes just before a human leaves may increase perceptions of privacy concerns in comparison to robots that keep their eyes always on. We did not obtain evidence that the perception of a robot's eyes being life-like correlates with privacy concerns.

Our findings provide important insights into how to design robots to be acceptable to households, and how the design of robot eyes may impact perceptions of privacy. Further, this is the first work to demonstrate how specific eye designs may increase privacy concerns, with our initial implications regarding eye design alternatives to mitigate this issue.

2 RELATED WORK

2.1 Privacy Concerns and Social Robots

Privacy, defined as "the claim of individuals, groups, or institutions to determine for themselves when, how, and to what extent information about them is communicated to others" [38], is ensured by the ability to determine one's environment without being controlled by the influence of intrusion from others. Altman defines privacy as "selective control of access to the self or to one's group" [1]. Therefore, an individual's privacy is expected to be protected in situations where they can selectively control access to information and space during social interactions with others. In the context of human- or life-like robot construction, privacy becomes a crucial psychological benchmark for success [17].

Privacy is multi-faceted. Smith et al. noted that in many research fields, there is often no clear distinction between physical privacy and informational privacy; they described physical privacy as including "access to an individual and/or the individual's surroundings and private space," while informational privacy was described as "access and control of personally identifiable information" [33]. In other words, physical privacy is secured by freedom from physical intrusion by others in the same space, and informational privacy is secured by freedom from intrusion into personally identifiable information. In the context of human-robot interaction, Lutz et al. categorized privacy into physical privacy and informational privacy and argued the need for robot designers to consider aspects of informational privacy [27]. Physical privacy relates to how the physical presence and movement of social robots affect personal space, while informational privacy relates to the robots' capacity to collect and process data, including control over third-party access such as manufacturers, hackers, other users, and third-party software providers [26].

Following, in this experiment, we define physical privacy between humans and robots as "the ability to control the physical intrusions to an individual that arise from being monitored by a robot" and informational privacy as "the ability to control intrusions into information by third parties through robots." As robots are unique entities that possess both life-like and data device characteristics, introducing robots into living spaces may pose concerns about both physical and informational privacy to the user. The social dimension of robots permeating public and private spaces can cause three dangers [24]. First, the introduction of social robots into living spaces may reduce opportunities for solitude and introspection. Second, robots having equal or greater information collection and accumulation capabilities than humans may promote data aggregation. Lastly, the sociability of robots, which can be controlled and adjusted by the owner, may become a new type of personal information. Specifically, introducing robots with eyes may pose a risk to solitude and introspection. This is because humans tend to act more socially when they are observed by a robot with eyes [9, 20, 29]. Additionally, it is suggested that as robots penetrate human life and gain the ability to monitor and record personal information, they may influence people's privacy consciousness [17].

In this experiment, we investigated the relationship between the design of a robot's eyes (appearance and behavior) and privacy concerns. Though perception of privacy is often closely linked to physical distance from others [1], the design of the robot is important: people tend to keep a larger distance from humanoid figures compared to identical-sized cylindrical objects [3], and keep humanoid robots at a greater distance compared to mechanical-appearing robots [34]. Further, research has demonstrated that humanoid robots are capable of gathering more private information than kiosks, which are stand-alone devices comprised of a tablet connected to a webcam [36].

Thus, the appearance of a robot in close proximity (e.g., whether they appear machine-like or life-like) may be relevant to perceptions of privacy. Based on this above work, we hypothesized that the more life-like the robot's appearance, the greater the privacy concerns would be.

2.2 Designing Robot Eyes

One's eyes are an important interface for expressing people's thoughts, feelings, and emotions [15]. Kendon argued that gaze has an "expressive function," and by expressing our emotions and attitudes through our gaze, we can control the behavior of others [21]. This is because eyes serve as a means of conveying our internal states and emotions.

Researchers have explored the use of human-like eyes for interaction with technology, for example, in the experiment by Osawa et al., a home appliance equipped with two eye-like modules that simulate human eyes, which gave instructions through pointing with gaze-drawing, achieved higher ability for indications [32]. In human-robot interaction, eye expression can help humans understand a robot's intention [37], impact perceived humanness [12], and identify facial expression in the eyes of a robot; facial expressions can be identified with a high degree of accuracy using only the linear features of the upper and lower eyes and mouth [6].

Specific elements of robot eye design include the eye size, eye shape, and pupil presence or absence. For example, a rounded outline shape and large iris can give a friendly impression [30], and overly large eyes can be intimidating and may intensify a sense of being watched [22]. According to a paper prototype experiment, the more life-like the robot's eyes are, the more personable and emotional the robot is perceived to be [25]. Kalegina et al. characterized and evaluated robots with rendered faces, finding that robots without pupils were perceived as less friendly and trustworthy, more disliked, and more machine-like than those with pupils [18].

In addition to how an eye looks, research has further explored how an eye should behave. The Kismet robot, which generated expressions using an emotion space, raised its upper eyelids for emotions with high arousal or open stance, such as "surprise" or "accepting," and squinted its eyelids for emotions with low arousal or closed stance, such as "tired" or "stern" [8]. Further, relating to physical distance, in one study female participants tended to keep more distance from an agent as the level of gaze behavior increased. This level of gaze behavior varies depending on its realism, with the lowest level having closed eyes and with higher levels including blinking with eyes open [3].

In addition, "black-screened eyes" (when a display is turned completely off or shows only black pixels) have a certain effect on emotions and personality traits. For example, for emotions like disgust or sadness, or a sleepy state, the less display light is shown, the higher the rating, and as the amount of light increases, the rating decreases monotonically [35]. In a stationary state where the robot does not move or talk, children may not recognize lights-out eyes as eyes [29].

Unlike humans, robots do not necessarily obtain visual information from their eyes, with many social robots having cameras located elsewhere. For example, the NAO robot's cameras are located in the forehead and mouth. Therefore, there is concern that "dishonest anthropomorphism" [19], such as a robot pretending to sleep while monitoring, may give a false bias with regard to information-gathering capacity [23]. Considering the important role that eyes play in how people interact with robots, we were motivated to investigate the influence of different eye states on the perception of robots. We specifically aimed to compare robots with open eyes, black eyes, and closed eyes. Our hypothesis is that these different eye conditions could influence a person's perceived privacy concerns and comfort, as well as more general perceptions of a robot.

3 ROBOT EYE PROTOTYPE

We created a robot prototype that is capable of a range of eye effects, such as being "open" and "closed," or turned off, to be manipulated for our study.

3.1 Hardware Design

The robot features a spherical shape with prominent eyes, as shown in Figure 2; we custom built the frame and incorporated an internal battery for power. We used animated graphical eyes on two circular screens, as opposed to mechanical eyes, following a recent trend in robotics (e.g., Aibo by Sony[1] and LOVOT by GROOVE X [2]). In the context of human-agent interaction, there have been attempts to create a wearable, glasses-type device that renders the users' eyes and shows gazes gestures [31]. This trend is perhaps due to reduction in screen costs and the significant challenges involved with building mechanical eyes.

The eyes are each equipped with 1.28-inch, 240×240-dot circular LCD panels, which we use to display the eyes. Each panel contains a separate microcontroller which communicates with a smartphone for remote control, and draws its power from the robot. We used a M5Stack M5Stamp C3 microcontroller, which incorporates the ESP32 C3; for clarity we refer to this simply as the "M5Stamp C3."

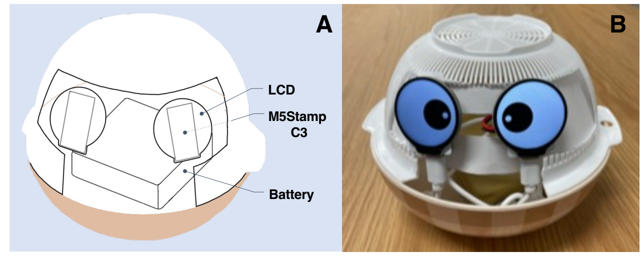


Figure 2: (A) M5stamp C3 microcontrollers are used to control an LCD display remotely through WiFi. (B) Robot prototype with covering removed; we used a felt-material skin cover for the experiment.

3.2 Software Design

We implemented a software system to allow remote control of the eye display and drawing. We programmed the microcontrollers using the Arduino language as a C++ library. The two microcontrollers operate in a server-client model, with one acting as a server to manage remote requests, such as from our smartphone. When a request is received it is relayed to the second, client, microcontroller, to enable trigger simultaneous state transitions on both devices. Communication between the server and client is facilitated through UART communication. Due to communication-based latency, we used a slight delay on the server display to ensure synchronous updates on both the left and right eyes.

The robot has three types of eyes: the open eyes, the black eyes, and the closed eyes. The open eyes are displayed as an image of circular eyes with pupils. The robot with the open eyes blinks randomly, and the average frequency of blinking is 40 times per minute. The blinking is an animation played on the display. The black eyes are displayed as a black image on the display. The transition between open eyes and black eyes is an instant image swap. The closed eyes image consists of a white background and eyelashes at the bottom of the image on the display. The transition between open eyes and closed eyes is an animation played on the display.

4 EXPERIMENTS

To investigate the impact of the robot's eye design on the perception of users' privacy, we designed a scenario-based experiment conducted on a crowdsourcing platform. In this experiment, participants watched videos of a human performing everyday tasks while being watched by our robot (see Section 3), and then completed questionnaires to report on their impressions. We employed a between-subjects video design where we presented each participant with only one condition, one of several versions of the video in which the robot's eye movements differed.

[1]https://aibo.sony.jp/
[2]https://lovot.life/

4.1 Conditions

In the experiment, we conducted a between-participants study with three conditions for the robot's eye: Always-on, Screen-off, and Closing-eyes.

4.1.1 Always-on (On) condition. This condition is designed to mimic a common robot behavior, with a robot's eyes always on, and we anticipate that it will give users the impression of constantly being watched, so the robot's eyes are open at all times.

4.1.2 Screen-off (Off) condition. This condition is designed to mimic a common method of disabling a robot's eyes, by the robot giving the impression of turning on and off the power (and thus stopping visual surveillance) when users are away by making the eyes black. When a person comes to the robot, the robot turns on the power and opens its eyes. When a person is about to leave, the robot powers off and closes its eyes.

4.1.3 Closing-eyes (Close) condition. This condition is designed to be a more natural solution following the metaphor of life-like eyes, for the robot to give the impression of stopping visual surveillance by closing its eyes when users are away. When a person comes to the robot, the robot opens its eyes. When a person is about to leave, the robot closes its eyes.

The hypotheses in this experiment were as follows:

- **H1**: The less life-like appear, the smaller the reported perception of privacy concern relating to a robot in one's living space.
- **H2**: Always-on eyes increase privacy concerns in relation to turned-off eyes, but this can be mitigated by a robot closing its eyes just before a user leaves the space.

4.2 Video Scenario

Participants were shown one of three different videos, each featuring a different type of robot. Before watching the video, participants read the following scenario:

"You will watch a video of a person and home robot living together in a room. You will then be asked to complete a questionnaire about living with the robot. Please imagine that you are actually living with the robot in the video in the room where you spend the most time at home, and answer as accurately as possible."

The video consists of a series of interactions in which a person sits down and reads a book in the direction of the robot's gaze and then leaves. The length of the video is 30 seconds for all conditions, and the person's actions are the same in each condition.

The video structure under this condition is as follows (shown in Figure 3): The video starts with the robot placed on a table. Five seconds after the video starts, a person appears from the right side of the screen and takes a seat in front of the robot. Under the Screen-off and Closing-eyes conditions, the robot turns to the on-state as the person sits down. Then, the person proceeds to open a book on the table and begins reading. During the reading, the scene fades to black to suggest the passage of time. Then, the person stands up, walks to the right side of the screen, and eventually disappears from the screen's view. In the Screen-off and Closing-eyes conditions, as the person stands up, the robot's eyes transition to the 'off-state'

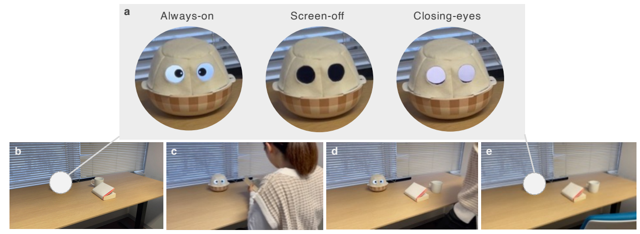


Figure 3: Video scenario, depicting the interaction between a robot with eyes and human in a living environment. Depending on the conditions, the robot's eyes vary (a) when a person is not present (b,e), but it is consistently on when a person is nearby (c,d). When the robot's eyes are in the on-state, it blinks randomly.

and 'sleep-state', respectively. From the beginning to end of the video, the robot maintains a constant direction.

4.3 Participants

We recruited participants using the Yahoo! crowdsourcing service. A total of 450 people participated in this between-subjects survey, divided into three groups of 150 each. We used a control question to check participant attention which required them to explain the robot's state at the end of the video in a free-form comment box. Those who gave clearly inappropriate answers to the control questions, those who used an unrealistically short time answering questions, and those who showed a consistent response behavior by selecting the same rating were removed from the analysis. The final valid response count was 420, with 142 in the Always-on condition, 145 in the Screen-off condition, and 133 in the Closing-eyes condition.

Of the 420 participants, 127 (30%) identified as female and 288 (69%) as male. Participants' ages ranged from 20 to 78, with a median of 49. 131 (31%) participants reported having talked to or played with a robot in the past.

4.4 Questionnaire

Participants answered questionnaires, including the Godspeed Questionnaire [4], Privacy Questionnaire (PQ), modified comfort with household activities (CHA) [10], and a free-response question describing the state of the robot's eyes at the end of the video.

The Godspeed Questionnaire is a widely used instrument to measure user perception of robots from five aspects: *Anthropomorphism, Animacy, Likability, Perceived intelligence,* and *Perceived safety*. Of these, Anthropomorphism, Animacy, and Likability are specifically related to visual features. This experiment focused on design in robot appearance, and the robots used in the experiment did not have specific functions that allow them to act intelligently. Therefore, among the five concepts, questionnaire items relating to Anthropomorphism, Animacy, and Likability were employed. All questions were based on a 5-point Likert-scale.

The Privacy Questionnaire (PQ) consisted of questions we created, based on the definitions of physical privacy and informational privacy described in Section 2.1. We asked participants questions about physical privacy (*"Do you have privacy concerns that you* *might be monitored by the robot?"*) and informational privacy (*"Do you have privacy concerns that someone might see your information through the robot?"*). For physical privacy, participants were asked about their concerns of being monitored by the robot, while for informational privacy, they were asked about their concerns that information might be accessed by someone else through the robot. Participants were prompted to respond to the extent of these concerns. All questions were based on a 7-point Likert-scale (1: *not at all*, 7: *very much*).

To assess levels of comfort, we used the modified comfort with household activities (CHA) questionnaire developed by Caine et al. [10]. CHA is rated from two different situations: general comfort level in the participant's home (pre-CHA) and comfort level considering the robot they saw in the video was being used in their home (post-CHA). Participants rated pre-CHA and post-CHA scores using a 7-point Likert-scale (1: *not at all comfortable*, 7: *very comfortable*). Then, we calculated the change socres(ΔCHA) by subtracting the post-CHA score from the pre-CHA score. ΔCHA was employed as a measure of discomfort associated with the robot's intrusion into their living space.

4.5 Procedure

Those who found our task on the crowdsourcing platform and visited the questionnaire link were first shown detailed information about the experiment task to seek informed consent for participation. Those who consented to participate were assigned to one of the three conditions and proceeded to a questionnaire page using Google Forms based on the scenario corresponding to the experimental condition. This questionnaire consisted of five sections: a preliminary questionnaire, which included questions to evaluate the pre-CHA, a section for describing the video scenario, a section for watching the video, and two evaluation sections. The evaluation sections included questions to assess post-CHA. After completing all questions, participants received a 7-character alphanumeric code on the survey submission completion page. They then returned to the web page within Yahoo! crowdsourcing and entered the received code into the form. If the correct code was entered, participants received their reward. Participants were given an incentive of points valued at 10 JPY (equivalent to US$ 0.10) for their participation. The viewing and response time for the videos was within 10 minutes, and participants were informed in advance that they would not receive a reward unless they completed all the questionnaires.

5 RESULTS

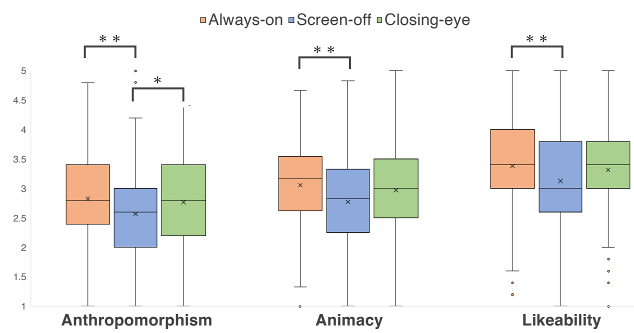
The Godspeed Questionnaire and PQ were analyzed with Kruskal Wallis and post-hoc Mann-Whitney-U tests with Holm correction. These tests were applied to each subscale of the Godspeed Questionnaire (Anthropomorphism, Animacy, and Likability) and each PQ item (Physical privacy and Informational privacy). For ΔCHA, following the testing method employed by Caine et al. [10], a one-way ANOVA was used to compare the three groups, and differences were identified. To further investigate any differences in ΔCHA, we conducted a post-hoc t-test with Holm correction.

Table 1: Mean values and standard deviations for each condition: Always-on (On), Screen-off (Off), and Closing-eyes (Close).

	Anthropomorphism	Animacy	Likeability
On	2.83 (0.71)	3.06 (0.73)	3.38 (0.69)
Off	2.57 (0.75)	2.78 (0.81)	3.13 (0.81)
Close	2.77 (0.75)	2.97 (0.79)	3.32 (0.76)

5.1 Godspeed Questionnaire

The mean and standard deviation for the three conditions are shown in Table 1. The Godspeed Questionnaire results for each condition are shown in Figure 4. Each item is evaluated on a 5-point Likert scale. As a result, the Always-on condition significantly increased in all items of Anthropomorphism, Animacy, and Likeability compared to the Screen-off condition ($p < .01$). Likewise, the Closing-eyes condition significantly increased in the Anthropomorphism item compared to the Screen-off condition ($p < .05$), while no significant difference was observed in Animacy and Likeability.



Note: $^{*}p < .05$, $^{**}p < .01$

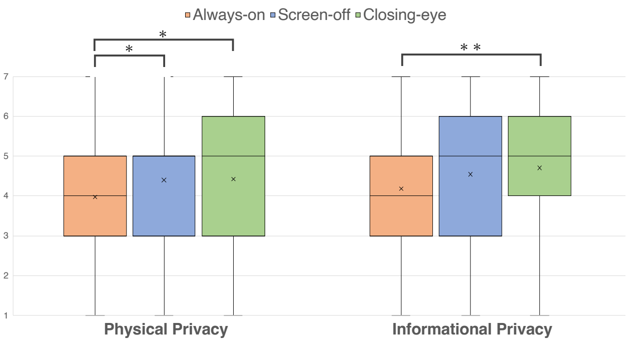
Figure 4: The Godspeed questionnaire: Anthropomorphism, Animacy, and Likeability

5.2 Privacy Concerns

The mean and standard deviation for the three conditions are shown in Table 2. The PQ scores for each condition are shown in Figure 5. Each item was rated on a 7-point Likert scale (1: *Not at all* 7: *Very much*), with higher values indicating greater concerns about privacy. For a significance level of $p = .05$, participants report significantly lower physical privacy concern in the Always-on condition than the Screen-off condition ($p < .01$), while no significant difference was observed in informational privacy ($p = .058$). Furthermore, the Always-on condition showed a statistically significant decrease in both physical and informational privacy compared to the Closing-eyes condition (physical privacy: $p < .05$, informational privacy: $p < .01$).

5.3 Comfort

The median and analysis of variance results for the three conditions are shown in Table 2. ΔCHA represents the decrease in comfort



Note: *p < .05, ** p < .01

Figure 5: Privacy concerns: higher is more concern.

Table 2: Privacy concerns and comfort associated with sharing living spaces with robots. The higher these scores, the more concern and uncomfortable, respectively.

(A) Privacy Concern			(B) Comfort	
	Physical	Information		ΔCHA
On	3.97 (1.63)	4.18 (1.52)	On	0.52 (1.40)
Off	4.40 (1.63)	4.54 (1.68)	Off	0.92 (1.65)
Close	4.43 (1.65)	4.71 (1.61)	Close	0.92 (1.37)

due to the introduction of a robot in the living space. It is important to note that the higher the ΔCHA, the more uncomfortable the participants felt about the idea of living with the robot. When the significance level was set at 5%, there was no significant difference among the conditions, but significant trends were observed between Always-on and Screen-off and between Always-on and Closing-eyes (p = .074).

5.4 Qualitative Results on the Robot Eye design

We analyzed qualitative data describing the robot's eye conditions following an inductive thematic analysis approach [7]. All responses were first coded, and the initial codes were sorted into sub-themes. They were then grouped into final themes so that the themes worked in relation to all codes. As a result, the evaluation of the robot's eyes was grouped into three categories.

5.4.1 Life-like Features. Participants associated the state of the robot's eyes with human characteristics and behavior. This was noticeable in Always-on (N=129; 91%) and Closing-eyes (N=115; 86%). In the Always-on condition, 44% of the participants described the robot as *"its eyes were open"* (P14), and 43% perceived it as *"it's blinking"* (P27). In the Closing-eyes condition, 68% of participants recognized the robot as "*its eyes were closed*" (P294). Meanwhile, in the Screen-off condition, fewer participants attributed life-like behaviors to the robot's eyes compared to the other conditions (N=45; 31%). Most of these participants (N=37) recognized the robot as "*its eyes were closed*"(P196); it appears that some participants perceived the robot's eyes as closed when its eye display was turned off.

Furthermore, there are responses implying the robot was "*watching*" or "*monitoring*" in all conditions (Always-on; N=7, Screen-off; N=5, Closing-eyes; N=9). Some participants described this from a third-party perspective, such as "*quietly watching with occasional blinking*" (P137) or "*watching a woman*" (P397). Others described themselves being observed by the robot, such as "*watching me*" (P63) or '*feeling like I'm being monitored*' (P170).

5.4.2 Visual Features. In contrast to life-like features, responses focusing on the visual features of the robot, such as shape and color, were notably more common in the Screen-off condition (N=110; 76%). The most frequent response was "*black*" (n=83), with others including "*lights off*" (N=14) and "*dark*" (N=8). Conversely, in Always-on (N=7; 5%) and Closing-eyes (N=14; 11%), there were noticeably fewer responses focusing on visual features. In both of these conditions, some responses included descriptions such as "*glowing*", "*round*", and "*white*".

5.4.3 Perception of robot. There were some responses that described perceptions of the robot, such as feelings and impressions. In the Always-on condition, there were several responses related to likeability, such as "*cute*" (P1, P12, 110), "*having a round and soft impression*" (P6), and "*anime-like*" (P92). Apart from these, a response of "*unable to understand its emotions*" (P117) was also noted. In the Screen-off condition, some participants had the impression that the robot was "*a little creepy*" (P146). Some participants also described their own feelings, such as "*fearful*" or "*uncomfortable*". One participant said, "*When it's off, it's all black and scary. I don't want to be with it.*" (P148). Other participants perceived "*power off*" (N=6) and "*I wondered if the power went off*" (P153). In the Closing-eyes condition, there were responses that described it as "*cute*" (P289), as in the Always-on condition. One participant also described, "*Somehow I felt a little lonely being all alone*" (P406).

5.5 Summary of Results

In this experiment, we investigated whether the perception of a robot's eyes being life-like correlates with privacy concerns (RQ1), and whether eye expressions that imply an inactive robot state can mitigate these concerns (RQ2). We hypothesized that the less life-like a robot's eyes appear, the smaller the reported perception of privacy concerns relating to a robot in one's living spaces (H1), and that robots with always-on eyes would increase privacy concerns in comparison to those with turned-off eyes, but this effect could be mitigated if the robot closed its eyes just before a user left the space (H2). To investigate these questions and hypotheses, we compared three conditions for the robot's eye: Always-on, Screen-off, and Closing-eyes.

In response to RQ2 and contrary to our hypothesis (H2), our results indicated that robots whose eyes turn off or close just before a human leaves can increase user privacy concerns compared to those with eyes that remain constantly open. Significantly higher physical privacy concern was reported in the Screen-off condition than the Always-on condition. The Closing-eyes condition also showed a statistically significant increase in both physical and informational privacy compared to the Always-on condition. This was an unexpected outcome, challenging our initial hypotheses and highlighting the complexity of user perceptions towards robot eye designs.

We found no direct correlation between the perception of a robot's eyes' life-likeness and privacy concerns (RQ1). The Screen-off condition resulted in a significant decrease in Anthropomorphism, Animacy, and Likability compared to the Always-on condition, and decreased Anthropomorphism significantly versus the Closing-eyes condition. Nonetheless, privacy concerns were higher in the Screen-off and Closing-eyes conditions compared to Always-on, despite no significant difference in informational privacy between the Screen-off and Always-on conditions. This outcome challenges H1 and suggests unexplored factors influencing user perceptions.

These results contribute to the ongoing conversation about privacy and user experience in robot design. They highlight the need for careful consideration of user perceptions. They also offer a fresh perspective on the role of life-likeness and eye expressions in shaping user experiences, setting a critical groundwork for future research in this area.

6 DISCUSSION

6.1 Life-like Eye Design

The results of the Godspeed Questionnaire showed that the robots of the Always-on condition and Closing-eyes condition had significantly higher Anthropomorphism than the robot of the Screen-off condition. Additionally, it was found that the always-on robot had significantly higher Animacy and Likeability compared to the robot in the Screen-off condition. This suggests that humans potentially place importance on visual information, particularly the eyes, when perceiving Anthropomorphism, Animacy, and Likeability of robots. This supports previous research findings that the robot's eyes are a means of communicating the perception of humanness [12] and intentions [37]. The robot with the Closing-eyes condition had higher Anthropomorphism than the robot with the Screen-off condition, suggesting that by rendering closed eyes, it may be possible to avoid the risk of the loss of Athropomorphism that comes with completely turning off the eyes. These results could be explained by the qualitative data regarding the perception of the robot's eyes. As most participants perceived the eyes of robots in the Always-on and Closing-eyes conditions as "open eyes" and "closed eyes", respectively, it is possible that these robots were considered more life-like compared to those that turned off the eye displays.

6.2 Privacy Concerns and Robot Eyes

Our hypothesis of H1 that "The less life-like appear, the smaller the reported perception of privacy concern relating to a robot in one's living space" was rejected, with no correlation found between Anthropomorphism or Animacy and privacy concerns. However, certain life-like interaction designs in robots could potentially have a negative impact on privacy. Our hypothesis of H2 that "Robots with always-on eyes increase privacy concerns in relation to turned-off eyes, but this can be mitigated by a robot closing its eyes just before a user leaves the space" was rejected; conversely, a robot closing its eyes increases privacy concerns compared to those with always-on eyes. This suggests that privacy concerns may be more influenced by the robot's functionality in responding to humans than by its appearance.

Responsive eye movements of robots have been shown to intensify gaze perception [39]; by changing the robot's gaze according to the partner's gaze, the feeling of being watched can be emphasized using a social robot. In this experiment, the gaze perception may have been intensified when the robot opened its eyes in response to a human compared to when the robot constantly had its eyes open. Indeed, in the Screen-off condition, we observed responses such as *"feel like I'm being monitored"*(P170), and in the Closing-eyes condition, we had responses such as *"It was glowing like I was being monitored"*(P364) and *"It is monitoring me."*(P365). However, in the Always-on condition, there were no responses that included the term "monitor." This increased visual intrusion may have led to privacy concerns. Esmark found that human proximity and direct gaze lead to increased anxiety and decreased satisfaction through loss of privacy control [14]. The results of this experiment suggest that concerns of physical privacy may be increased by the visual intrusion of robots.

The results regarding informational privacy showed a slight difference from those concerning physical privacy. Specifically, in the Screen-off condition, the concerns about informational privacy only tended to be significant, unlike in the Closing-eyes condition, where the concerns were significantly higher than in the Always-on condition. Informational privacy can be threatened by the increased data collecting capacity of social robots [26]. However, robots with their eyes screened off may have been perceived as powered off, thereby not raising as many concerns as robots with their eyes closed. This hypothesis suggests a nuanced relationship between the appearance of robots and privacy concerns, and it warrants further investigation.

Additionally, the results of comfort showed that comfort tends to be lower when privacy concerns are higher. This suggests that discomfort may be caused by privacy concerns for the robot. Our findings suggest that the interactive eye may negatively affect privacy. When designers give robots eyes, they need to consider the privacy implications and try to ensure that the perception of being monitored is not uncomfortable.

6.3 Limitations

In this experiment, there were several constraints and considerations. First, there is a possibility that some participants did not correctly recognize the eye state. The questionnaire regarding the robot's eye state had a few responses such as "white eyes" and "empty eyes" for the Closing-eyes condition. These responses suggest that the closed-eye state was not properly conveyed to some participants. However, it cannot be denied that these may be inappropriate responses from participants who did not watch the video to the end (these participants were considered valid respondents).

Furthermore, there may have been variations among participants in the context of using the robot. In this experiment, participants were instructed to *"imagine that you are actually living with the robot in the video"*, and *"please answer as accurately as possible"* before watching the video and answering the questionnaire. Because participants answered after watching the video, the scenario may have influenced them, resulting in a loss of originality in their imagination. Additionally, considering the different living environments of the participants, the location for using the robot was not explicitly specified but designated as *"the room in your home where you spend the most time."* Therefore, the context of actually living with the robot might have varied among participants. Some participants may not have fully considered the impact on privacy due to sharing living space with the robot.

Future research should address the constraints identified in this study by crafting improved experimental scenarios. Although the present design had limitations, it provided valuable insights into privacy-friendly design that can potentially resolve privacy issues. One promising direction stems from the robot's eyes being equipped with displays, allowing for the exploration of a more diverse range of eye designs. By delving deeper into this area and conducting a more extensive exploration of design possibilities, we may identify solutions that are even more considerate of privacy concerns.

6.4 Design Implications

The results of this research offer crucial insights for enhancing privacy-related user experience in robot design. The first implication concerns the significance of appearance-functionality consistency. The fact that eye expressions indicating a robot's state (e.g., screen-off or closing-eyes) increased user privacy concerns suggests that it's critical for a robot's visual display and the functionality it implies to align. This assists people in accurately understanding and predicting a robot's behavior. Secondly, it's important to enable users to control the robot's operational state themselves such as its active/sleep/inactive mode. Esmark et al. conducted research on human-human interactions, showing that when humans are subjected to close proximity or direct gaze from others, privacy control decreases, leading to increased anxiety and decreased satisfaction [14]. The insights from this study on human interactions can be applied to the interactions between humans and robots. Robots that automatically open their eyes, without allowing users to control this action, may similarly raise concerns due to the lack of privacy controls over the robot's visual perception. By allowing users to control a robot's status, such as transitioning from sleep mode to active mode, these concerns can be mitigated. Lastly, a robot's privacy practices should be clear to users. Margot et al. stated that one of the principles in privacy design for home robots is honest anthropomorphism (*"robot designers should not use anthropomorphism to mislead users as to privacy practices deliberately"*) [19]. Our study suggested that the fact of screen-off or closing-eyes indicating privacy-protective behavior might not have been understood by users. Privacy practices should be conveyed to users clearly, through explicit or implicit feedback from the robot. However, obtaining informed consent with social robots is challenging, and this suggests a need for "visceral notice" and nudges rather than traditional notifications and consent [26]. Our experimental results reveal that eye expressions can influence privacy concerns, serving as a preliminary step that suggests the potential of using eye expressions as intuitive feedback to enhance transparency in robots.

7 CONCLUSION

We investigated a privacy-friendly design of robot eyes for social robots that share living spaces. To understand its impact on human perception of privacy, we compared a robot that constantly opens its eyes to one that only opens its eyes during interaction. The results showed that the robot opening its eyes only during the interaction induced higher privacy concerns. While no significant differences were observed regarding comfort levels living with either robot, the possibility arose that living with a robot that opened its eyes only during interaction could be less comfortable.

While our research suggests that humans may be influenced by the visual information received from a robot's eyes in their perception of the robot, we did not find that the life-like appearance of the eyes directly affected perceptions of privacy. However, we found that the interactive behavior of changing the appearance of the eyes in response to humans might increase privacy concerns. Further investigation is needed to achieve a design that balances eye communication and consideration of privacy.

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