Bioluminescence-Inspired Human-Robot Interaction

Designing Expressive Lights that Affect Human's Willingness to Interact with a Robot

Sichao Song
The Graduate University for Advanced Studies
(SOKENDAI), Department of Informatics
2-1-2 Hitotsubashi, Chiyoda, Tokyo, Japan
sichaos@nii.ac.jp

Seiji Yamada
National Institute of Informatics and SOKENDAI
2-1-2 Hitotsubashi, Chiyoda, Tokyo, Japan
seiji@nii.ac.jp

ABSTRACT

Bioluminescence is the production and emission of light by a living organism. It, as a means of communication, is of importance for the survival of various creatures. Inspired by bioluminescent light behaviors, we explore the design of expressive lights and evaluate the effect of such expressions on a human's perception of and attitude toward an appearance-constrained robot. Such robots are in urgent need of finding effective ways to present themselves and communicate their intentions due to a lack of social expressivity. We particularly focus on the expression of attractiveness and hostility because a robot would need to be able to attract or keep away human users in practical human-robot interaction (HRI) scenarios. In this work, we installed an LED lighting system on a Roomba robot and conducted a series of two experiments. We first worked through a structured approach to determine the best light expression designs for the robot to show attractiveness and hostility. This resulted in four recommended light expressions. Further, we performed a verification study to examine the effectiveness of such light expressions in a typical HRI context. On the basis of the findings, we offer design guidelines for expressive lights that HRI researchers and practitioners could readily employ.

KEYWORDS

Bioluminescence; expressive lights; attractiveness; hostility; color psychology; appearance-constrained robot; human-robot interaction (HRI)

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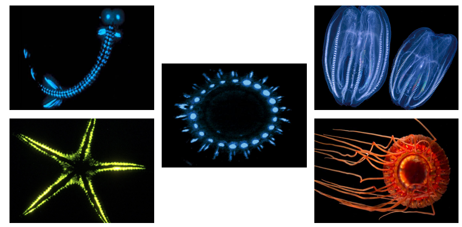

Figure 1: Examples of bioluminescent organisms

1 INTRODUCTION

Bioluminescence is the production and emission of light by a living organism [4]. The majority of bioluminescent organisms reside in the ocean as about 80% of the genera known to contain luminous species are marine, including, for instance, luminescent fish, e.g., mycophids and hatchetfish, and crustaceans, e.g., copepods and krill) [5]. In addition, bioluminescence occurs in some fungi and terrestrial invertebrates, such as fireflies, as well (Figure 1). A large number of organisms retain functional eyes to detect bioluminescence in dark environments, which suggests the importance of bioluminescence as a means of communication for the survival of a vast variety of creatures [5].

Appearance-constrained robots, in comparison, reside in a similar situation as bioluminescent organisms. These robots are designed to be functional and lack expressive faces [30]. Although they primarily work in bright places, their lack of social expressivity makes it hard for them to be perceived and understood by humans. As a result, people are in a way "blind" to appearance-constrained robots. In human-robot interaction (HRI) scenarios, this can lead to unsmooth or even failed interaction [28]. As if they were bioluminescent organisms in the dark, appearance-constrained robots are in urgent need of finding effective ways to present themselves and communicate their intentions.

Because of the restricted interaction modality of appearance-constrained robots, current approaches rely mainly on motion cues [11, 12, 15, 34, 42]. Unfortunately, these approaches are limited in expressivity and are hard to apply in many practical scenarios. For instance, it can be impossible for a robot to use big movements, e.g., acceleration and moving in an arc, to interact with human users when situated in a crowded room. To address such limitations, we investigate expressive lights as an alternative interaction modality. By using expressive lights, we are enabling a robot to modify its appearance as a means of communicating with humans.

Expressive lights as a dynamic visual cue have been explored for HRI applications. For instance, Sony's robot dog AIBO[1] and Aldebaran's NAO[2] use LED lights to assist in affective expression.

[1] http://www.sony-aibo.com
[2] http://www.ald.softbankrobotics.com/en/robots/nao

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In general, expressive lights have been shown to be effective in various HRI contexts such as indicating internal states [7], communicating intent [43], and expressing emotion [13]. The goals of using expressive lights on a social robot could be summarized by the three I's: Inform, Influence, and Interact [7]. Specifically, *Inform* is about showing a robot's internal state, *Influence* is about changing human behavior to a robot's advantage, and *Interact* is about affective communication and interaction. Most current research has mainly been relevant to *Inform*, and the other two components, *Influence* and *Interact*, have seldom been touched upon. It is therefore important to encourage further exploration on the use of expressive lights.

Bioluminescence provides good inspiration. Basically, luminescence can serve three purposes within a single organism: offense, e.g., attracting prey, defense, e.g., warning a predator, and mate attraction [19]. With regard to HRI, we think that a robot may need to possess two general social abilities: initialize or escape from an interaction. The importance of a robot initializing an interaction is evident in the vast applications of social robots. For instance, a service/guide robot needs to proactively approach customers/visitors to promote successful interactions as previous research suggests that potential interaction opportunities, e.g., with people that hesitate about whether or not they will engage a robot, may be missed if the robot is inactive [24, 41]. In addition, a robot needs to escape from a potentially harmful interaction as well. As reported by a few pieces of literature, robots may physically get abused by humans [8, 10, 40]. In such cases, we compare a potential target human to prey when a robot approaches him or her proactively. Similarly, we compare a potentially dangerous human to a predator when he or she approaches the robot. Inspired by the functions of bioluminescence, we accordingly consider that such a robot needs to either attract its target humans (offense) or warn the dangerous ones to keep their distance (defense).

In this work, we primarily explore the design of expressive lights to achieve such goals. Specifically, we aim at designing expressive lights that are either perceived as **attractive** or **hostile**. We presume that a robot that is perceived as attractive may do a better job at initializing an interaction, whereas a robot that is perceived as hostile may reduce a human's willingness to interact with it. On the basis of inspiration from bioluminescence and color psychology theories, we work through a structured process to determine a set of effective light expressions. A follow-up video-based validation study is then performed to verify the effectiveness of the light expressions in practical HRI scenarios. Our work can serve as an extension of [7, 43] and suggests potential effects of expressive lights on influencing people's perception and behavior, therefore increasing exploration on the use of expressive lights in HRI.

2 BACKGROUND

2.1 Appearance-Constrained Robot

Affective interaction has become an active topic in social robotics and HRI [9]. However, major studies on it have been focused on human- and animal-like robots [9, 16]. There is a lack of methods that appearance-constrained robots can use to express affect. Such methods are in eager need, as many currently-in-use robots are restricted in appearance, while there is a need for them to be capable of affective interaction [31].

A number of studies have been carried out to explore the design of non-facial/non-verbal affective expressions [28–31]. The authors claimed that appearance-constrained robots are not engineered to be anthropomorphic due to either there being limited applications or for cost-saving reasons. They highlighted the importance for such robots to express emotions. For instance, rescue workers were found to expect a small tank-like robot to follow social conventions [14]; man-packable robots were observed to be perceived as "creepy" and not reassuring when they were operated close to simulated victims [38].

Although these pieces of work provide insights into affective social interaction between humans and appearance-constrained robots, there are several limitations with regard to the generality of their findings. As they focused on application scenarios involving assessing victims in the aftermath of a disaster, their results were majorly based on simulated human victims interacting with two types of search and rescue robots [28]. Therefore, their methods can be hard to generalize to other types of robots, e.g., Roomba, and practical scenarios. In addition, since they used only blue light as an auxiliary expression to elicit a calming response, they thus offered open research questions such as "Can illuminated colored lighting effects be used effectively to convey affect and for naturalistic social human robot interactions?" [28]. These questions are ones that we try to solve.

2.2 Initialize or Escape from Interaction

We think that a social robot needs to have two basic social abilities: to initialize or escape from a potential interaction. How a robot should approach humans and try to successfully establish an interaction has been an active topic. Scenarios involving public service, e.g., an information center in a shopping mall, have been particularly researched [24, 41]. In many cases, if a robot only passively waits for a human user to initiate an interaction with it, people who are hesitating or unsure of how to interact would be not served [24]. Thus, it is of importance to allow a robot to proactively approach target humans. To achieve such a goal, the robot needs methods to attract target people so as to increase the possibility of successfully establishing interactions with them.

In addition, a handful of studies have investigated robot abuse [8, 10, 40]. It is reported that people, children in particular, tend to react to robots with high curiosity and often treat them aggressively [10, 40]. Abuse behaviors include saying bad things to the robots and sometimes even kicking or punching them [10]. Therefore, robots in such situations need to be able to escape from human abuse.

2.3 Bioluminescence Functions

The many functions of bioluminescence reflect the unique nature of the environment in which a vast variety of bioluminescent organisms have evolved [5]. Basically, luminescence can serve three purposes within a single organism: offense, e.g., attract prey, defense, e.g., warning predators, and mate attraction [19]. For example, bioluminescent creatures, e.g., dinoflagellates and squid, use light to startle a predator in order to defend themselves from being

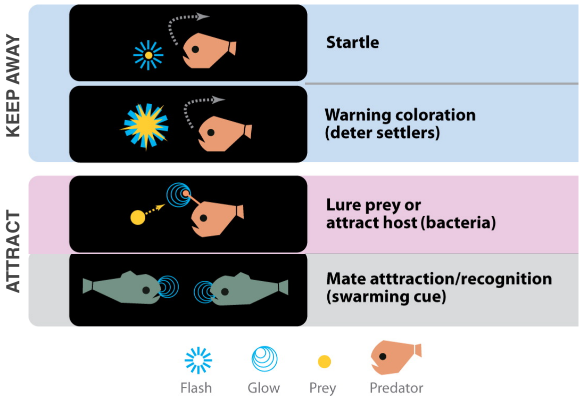

Figure 2: Two general functions of bioluminescence: attraction and keeping away (adapted from [19])

preyed upon. Some predators, e.g., anglerfish, use light to lure their prey. Many creatures, e.g., ostracodes and flashlight fish, rely on bioluminescent light to attract and recognize their mates [19]. In general, bioluminescence functions can be summarized into two kinds: those that attract or keep others away (Figure 2).

With regard to the two HRI scenarios we focus on in this work, that is, initialize and escape from an interaction, we think that a robot, similarly, should be able to attract or keep humans away. To be specific, a robot needs to attract human users to successfully establish an interaction, whereas it needs to keep unfriendly people away to escape from abuse.

2.4 Expressive Lights for Robots

Expressive lights, as an explicit way of communication, have been discussed in studies across various fields such as psychology [17, 35], human-computer interaction (HCI) [18, 25, 36, 37], and human-robot interaction [7, 26, 43]. To be specific, it is suggested that even simple light expressions can be highly expressive [18] and are able to evoke high-level social and emotional content [25, 37]. Such artificial lights in different colors can implicitly affect human perception and psychological functioning and therefore may influence human behavior [17, 35].

With regard to HRI scenarios, a majority of work focuses on human-oriented applications because one fundamental goal of social robots is to serve people. Expressive lights have been considered as an effective approach for non-verbal communication, and such an approach is considered to be particularly useful for appearance-constrained robots, as such robots generally have very low social expressivity [30]. Several studies have investigated potential functional uses of lights for robots. For instance, expressive light animations were applied to visualize a mobile service robot's internal state [7]. The authors designed different light patterns to indicate that the robot is waiting for human input, is being blocked by a human, or is showing task progress. Another work [43] explored design constrains to robot flight behaviors. Their designed light expressions were able to significantly improve people's response time and accuracy for predicting the flying direction of the robot.

Research on expressive lights for HRI is still in its infancy. It is suggested that the goals of using expressive lights on social robots can be summarized by the three I's: Inform, Influence, and Interact [7]. Despite the many promising studies that have been done in this area, they mainly touched on the first component only. Therefore, both theoretical and empirical work regarding the design of expressive lights are needed to provide building blocks for more sophisticated and interaction-oriented HRI.

3 EXPRESSIVE LIGHT DESIGN

3.1 Exploring Design Space

3.1.1 Color. Although the RGB color space contains tens of thousands of colors, we only consider categorical colors, e.g., green and red, due to their simplicity and representativeness. In addition, this is valid as the human color vision system processes color signals in a categorically driven manner [21]. Color psychologists have intensively investigated various aspects of color, including color vision, color symbolism and association, and the effects of color on psychological and biological functioning [21]. Basically, their work primarily focuses on red, blue, and green since such colors (especially red) have been considered to be special and have positive links to the natural realm.

On one hand, *associative learning theory* provides a promising explanation of color-emotion associations [22]. According to this theory, color meanings are grounded in two basic sources: learned associations that develop from repeated pairings of colors with particular messages, concepts, or experiences and biologically based proclivities to respond to particular colors in particular ways in particular situations [22]. For example, red carries the meaning of danger and anger in life-threatening situations, such as when viewing blood, an angry face, traffic lights, and/or warning signals and sirens [23]. Similarly, green can be associated with positive meanings due to traffic lights (green light indicates "go") and an image of being the color of nature. Blue can be associated with sadness due to the saying "I feel blue" [23].

On the other hand, *mental alertness theory* suggests that color can affect a person's level of mental alertness and therefore influence his or her psychological functioning [20]. Previous work indicates that red makes people more alert and risk averse, whereas blue encourages people to take risks and perform exploratory behaviors [17]. In addition, blue light is able to elicit pleasure [35] and creativity [39]. These findings indicate that the color blue can be attractive to humans.

In addition, previous studies observed that exposure to green and blue evokes lower feelings of anxiety and greater feelings of calmness [6]. It has long been proposed that being exposed to colors with longer wavelengths such as red and yellow is stimulating and arousing, whereas shorter wavelength colors, such as green and blue, tend to evoke feelings of calmness and tranquility [6].

3.1.2 Patterns. Due to the shape of the LED strip, the design space of a light expression pattern is restricted to one dimension. However, because each LED pixel can be individually controlled, finding desirable designs is still challenging. To cover a wide range of possible light expressions, we primarily investigated two types of patterns: strip-based patterns and pixel-based ones. The former

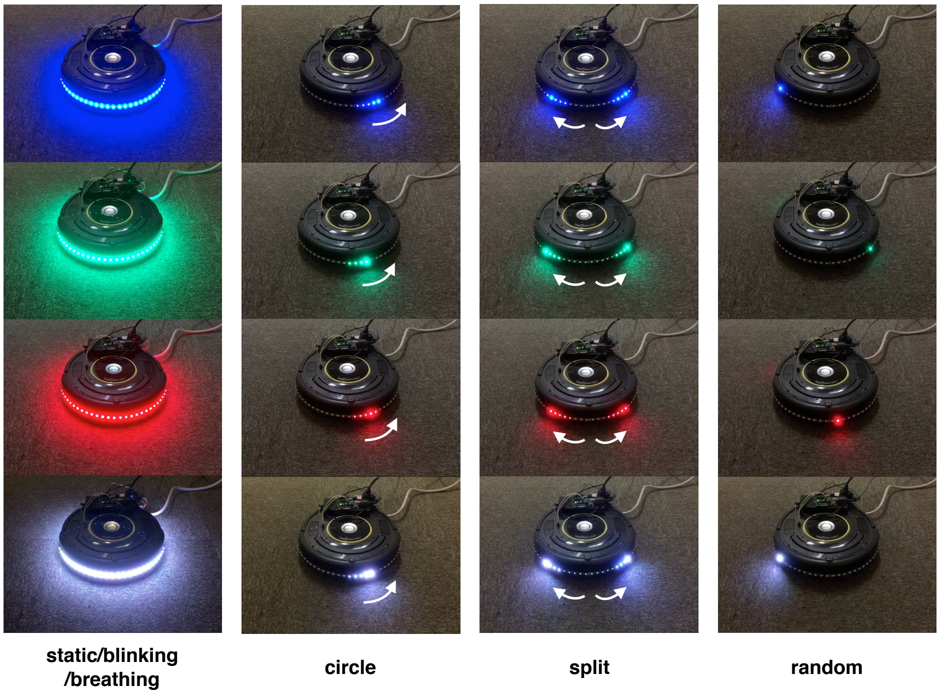

Figure 3: Demonstrations of candidate expressive light patterns. All, except static, were periodic. Each periodic expressive light pattern consisted of five periods. For random pattern, singular random pixels in the LED strip were turned on and off throughout the given time period

includes light expressions that make use of all LED pixels as a whole (the entire LED strip), whereas the latter consists of light expressions that take advantage of individual LED pixel expressions.

During her speech at TED2011[3], Edith Widder demonstrated plenty of bioluminescent light behaviors performed by sea creatures. Inspired by such natural bioluminescent lights, we designed a set of representative light patterns. To be specific, a pattern can have two parameters: waveform and intensity (frequency). Existing findings suggest that a rectangular waveform and high intensity represent intense emotions, while a sinusoidal waveform and low intensity represent weak emotions [44]. Therefore, with regard to strip-based patterns, we explored both rectangular (named *blinking*) and sinusoidal (named *breathing*) waveforms with low and high frequencies, respectively. In addition, a *static* pattern, in which the entire LED strip is always lit, was also chosen. With regard to pixel-based patterns, the waveform parameters for individual LED pixels were not considered. We chose three patterns: *circle*, *split*, and *random*. It is notable that, for the random pattern, singular random pixels in the LED strip were turned on and off throughout the given time period.

3.2 Candidate Expressive Lights

We decided on 44 light expressions in total as our expressive light candidates (Figure 3). In summary, they made use of four colors (red, green, blue, white), five patterns (blinking, breathing, circle, split, random) with two intensities (low, high), and one special pattern (static). All light expressions, except static, were periodic, and each corresponding expressive light contained five periods. We designed a large number of expressive light patterns in the hope of covering a wide range of potential light expressions.

3.3 Roomba Lighting System

We installed an LED lighting system on an iRobot Create 2 robot. Roomba is a series of indoor autonomous robotic vacuum cleaners.

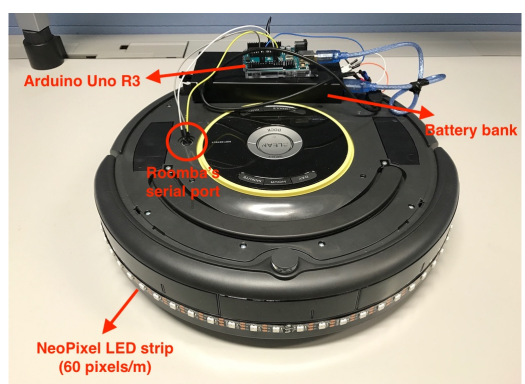

Figure 4: Configuration of Roomba robot with LED lighting system

[3]See https://www.ted.com/talks/edith_widder_the_weird_and_wonderful_world_of_bioluminescence#t-112245.

All Roomba robots are disc-shaped, 34 cm in diameter, and less than 9 cm in height [3]. iRobot Create 2 is a programmable Roomba robot for educators, students, and developers [2]. Therefore, it allows for a variety of programming methods and can be connected to a microcontroller. We think that such a robot perfectly meets the definition of an appearance-constrained robot, and in addition, has limited methods of expressing affect, e.g., moving forward/backward and spinning.

Figure 4 illustrates the configuration of the Roomba robot with the LED strip. Following the design of [43], we attached a NeoPixel LED strip (1 meter, 60 pixels) to the body of the robot in a ring. The strip was controlled by an Arduino Uno R3 board, where the data pin of the strip was connected to the digital output pin of the Arduino board. Both the strip and board were powered by a 5-V, 3-A portable powerbank. In addition, the same board was used to control the movements of the Roomba robot as well. iRobot Create 2 provides the Roomba Open Interface (OI) [1] which is a software interface for controlling and manipulating Roomba's behavior.

4 EXPERIMENT

4.1 Procedure

We aimed at finding a set of appropriate expressive lights that can allow the Roomba robot to be perceived as either attractive or hostile by humans. To ensure the generality of the experimental results, having a large and diverse set of participants was important. Therefore, we employed a Japanese online crowdsourcing platform Fastask to recruit participants for the experiment. Recent studies, e.g., [18, 27], have shown the validity and power of crowd-sourced approaches. It allowed us to rapidly and inexpensively gather data from many more participants than would have been practical with other approaches. Data integrity was guaranteed by dropping participants whose answers had near-zero variances, e.g., all 3's. As a result, a total of 27 of them were discarded, leaving data from 73 participants (23 females, M_{age} =48.04, SD_{age} =14.12). All participants were native Japanese speakers.

We used video recordings to demonstrate all the candidate expressive lights. For each video, we provided two statements to evaluate the participants' perception of the robot: "This robot looks attractive" and "This robot looks hostile." A five-point Likert scale was used for the statements (ranging from 1, strongly disagree, up to 5, strongly agree). Each participant in the study viewed all 44 videos and rated them one at a time (within-participant design), and the order of the videos was randomized.

4.2 Criteria

We analyzed the candidate expressive lights with regard to the two perceptions, attractive and hostile, separately. For the evaluation, we introduced two criteria (adapted from [18]) to select good light expressions: 1) an expression must have a strong interpretation with regard to a perception (mean Likert rating in the top quartile) and 2) an expression must be iconic, meaning that it has only one dominant perception among the two (an expression should not be perceived as both attractive and hostile). We assessed the iconicness of each candidate expression that meets criteria 1.

4.3 Results

We summarized the ratings from all 73 participants. Figures 5 and 6 show the mean Likert ratings for attractive and hostile, respectively. Because we used a single Likert term rather than constructed scales to assess human perception, statistic measures, such as ANOVA, were not appropriate. Instead, we characterized the main trends observed in the data and reported on them with regard to each perception.

Attractive: We recommend *split_blue_low* (a low-intensity blue split pattern) and *circle_blue_low* (a low-intensity blue circle pattern) for showing attractiveness. These are iconic and the top two highest-rated light expressions (see Fig. 5). The commonality between the two light expressions is straightforward in that they both feature the color blue and have a low intensity. In general, it can be observed that expressive lights with one or more of the following three features received high ratings from the participants: 1) blue, 2) low intensity, 3) pixel-based patterns (particularly split and circle ones). On the other hand, expressive lights with one or more of the

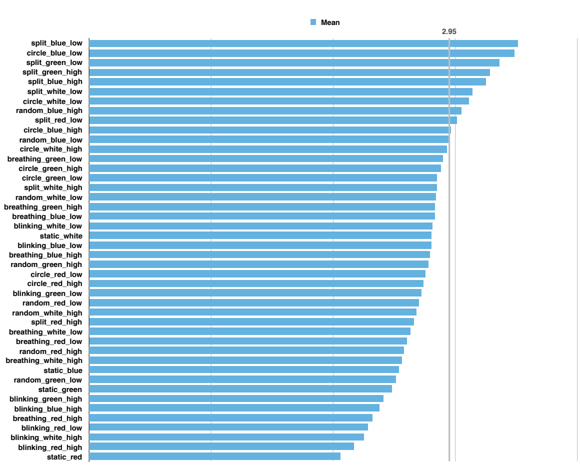

Figure 5: Mean Likert ratings for attractive perception.

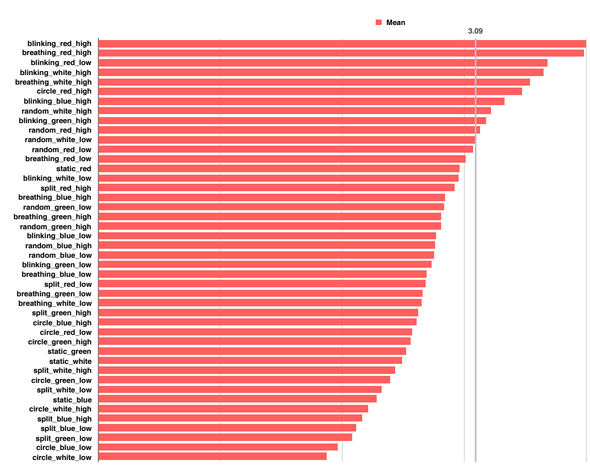

Figure 6: Mean Likert ratings for hostile perception.

following three features received low ratings for attractiveness: 1) red, 2) high intensity, 3) strip-based patterns.

Hostile: We recommend *blinking_red_high* (a high-intensity red blinking pattern) and *breathing_red_high* (a high-intensity red breathing pattern) for showing hostility. These are iconic and the top two highest-rated light expressions (see Fig. 6). The commonality between the two light expressions is clear in that they both feature the color red and have a high intensity. In general, several trends can be observed that show that expressive lights with one or more of the following features received high ratings: 1) red, 2) high intensity, 3) strip-based patterns (particularly blinking and breathing). Oppositely, expressive lights with one or more of the following features received low ratings for hostility: 1) low intensity, 2) pixel-based patterns (particularly split and circle ones).

4.4 Discussion

Four expressive lights were selected as effective expressions for the Roomba robot to show either attractiveness or hostility. The results offer strong evidence, indicating that expressive lights can effectively affect a human's perception of a robot. To be specific, we found that the robot was particularly attractive when showing blue light at a low intensity. In addition, the split and circle patterns turned out to be more absorbing compared with the other patterns. We also found that the robot was perceived as particularly hostile when showing red light at a high intensity. Both blinking (rectangular) and breathing (sinusoidal) patterns were selected, suggesting that waveform was a less important factor compared with color and intensity (frequency). However, it is noticeable that the two patterns are strip-based patterns. This indicates that high luminance may be of importance for showing hostility as well.

Interestingly, features of these four expressive lights can be observed in a variety of bioluminescent ocean creatures. Edith Widder demonstrated plenty of bioluminescent light behaviors performed by sea creatures, where many of them showed similar patterns. This indicates that bioluminescent lights used by natural creatures may have analogous effects on human perception and psychological functioning. In addition, the results are in line with color psychology theories. As suggested by color psychology literature [17, 39], red carries the meaning of danger and hostility and moreover makes people more alert and risk averse, whereas blue elicits pleasure and encourages people to take risks. Therefore, it can be presumed that blue light, in many situations, is more attractive than other colors, while red light conveys a negative effect.

5 FOLLOW-UP VERIFICATION STUDY

As we worked through a structured process for designing affective expressive lights, we were able to offer a set of four light expressions that can well show attractiveness and hostility. However, the effectiveness of such lights had not yet been examined in practical HRI scenarios. Therefore, we further conducted a verification experiment in which the same Roomba robot with LED lighting system was employed. In the follow-up study, we evaluated the effectiveness of the recommended light expressions by observing whether people would be willing to approach and interact with the robot when it showed attractiveness and whether they would consider keeping away from it when it showed hostility.

5.1 Procedure

We designed two HRI scenarios: *robot approaches human (RH)* and *human approaches robot (HR)*. To be specific, in RH, the Roomba robot moved toward a person (experimenter) proactively, whereas, in HR, the person moved toward the robot. Particularly in HR, the robot started to show expressive lights when the person was within about 2 m. RH was designed to simulate a scenario in which a robot tries to initiate an interaction with a person, and HR was to simulate a scenario in which a robot is approached by an unwanted person.

We employed the same Japanese online crowdsourcing platform to recruit participants for this study. Video recordings were used to demonstrate the two HRI scenarios via an online survey. For each scenario, we provided one synthetic video involving three conditions: the robot showing attractiveness, the robot showing hostility, and the robot not showing any expressive light. With regard to the attractiveness condition, we picked *split_blue_low* as the representative light expression. Similarly, we chose *blinking_red_high* as the representative light expression for the hostility condition.

Figure 7 shows screenshots of each video clip. It is notable that although the screenshots show a large difference in distance between the camera and the robot regarding the two scenarios (RH and HR), this was due to the different timings of taking these screenshots. In RH, the robot is close to the person, which shows the effect of the robot's approach behavior (the robot has moved a long distance from its original position). Similarly in HR, the person is seen standing close to the robot, which indicates the person's approach behavior (the person has moved a long distance from his original position). The order of the three clips for each scenario was randomized. Participants whose responses had near-zero variances were removed from the results evaluation. In total, 16 of them were discarded, leaving data from 205 participants (68 female, M_{age} =50.97, SD_{age} =13.03). All the participants were Japanese.

With regard to each synthetic video, we prepared four statements to evaluate the participants' perception of and attitude toward

Figure 7: Screenshots of each video clip (condition)

the robot: 1) "This robot looks attractive," 2) "This robot looks hostile," 3) "I like this robot," 4a) "I want to play with this robot" (RH scenario), and 4b) "I want to keep away from this robot" (HR scenario). For each statement, the participants were asked to choose the robot presented in one of the three conditions that best fit the statements. The selection rate (SR) was counted for each condition. The SR number, ranging from 0 to 205 (total amount of participants), indicated how many participants chose a robot for a particular statement. Similar approaches were used in other studies, e.g., [7].

5.2 Results

We applied Pearson's chi-square test to evaluate the effect of the independent factor (expressive light) on the five statements as dependent factors. A post-hoc binomial test with Holm's correction was further applied if a significant difference was found. Because of the three conditions, the hypothesized probability that each condition would be chosen at random with regard to a statement was set to one-third (33.33%, which is the probability of a random guess).

Figure 8 shows the selection rates with regard to the participants' perception of the robot. For each statement, a significant difference was found for both the RH scenario (attractive: $\chi^2(2) = 157.09, p < 0.001$; hostile: $\chi^2(2) = 203.01, p < 0.001$; likeable: $\chi^2(2) = 123.11, p < 0.001$; want-to-interact: $\chi^2(2) = 113.98, p < 0.001$) and the HR scenario (attractive: $\chi^2(2) = 129.02, p < 0.001$; hostile: $\chi^2(2) = 211.5, p < 0.001$; likeable: $\chi^2(2) = 180.71, p < 0.001$; want-to-interact: $\chi^2(2) = 71.22, p < 0.001$). The post-hoc tests suggest that the conditions with the top SR, e.g., split_blue_low for *attractive* and blinking_red_high for *hostile*, were selected as the ones that most fit the corresponding statements (significantly above 33.33%, $p < 0.001$), while the SRs for the other conditions were all significantly below 33.33% ($p < 0.001$).

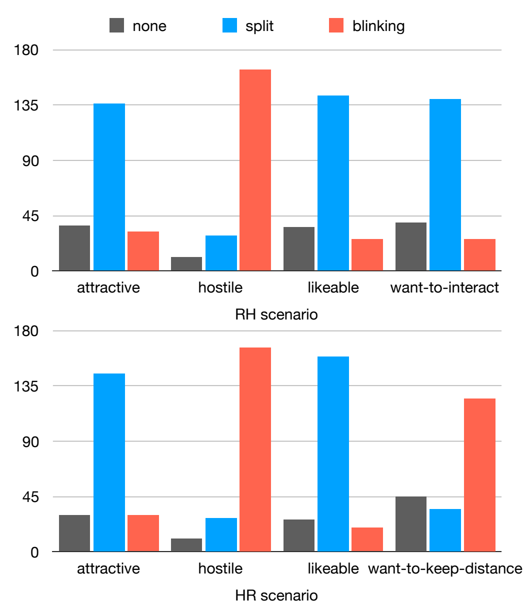

Figure 8: Selection rates for each statement for RH scenario (above) and HR scenario (below)

5.3 Discussion

The results verify the effectiveness of our recommended expressive lights on people's perception of a robot. The robot showed that split_blue_low was particularly perceived as attractive and preferred by the participants, while it was perceived as hostile when showing blinking_red_high. This meets our expectation as expressive light split_blue_low was recommended to show attractiveness and blinking_red_high was recommended to show hostility. Moreover, the participants' attitudes toward the robot was influenced as they preferred to play/interact with the robot when it showed split_blue_low, whereas they considered keeping their distance from the robot when it showed blinking_red_high.

6 GENERAL DISCUSSION

This work explored the design of expressive lights for a Roomba robot to influence humans' willingness to interact with it. The goal was to allow robots to either attract people so that they can more easily initialize an interaction with them, or keep people away so that they can escape from a potentially harmful interaction. Our work expands on previous studies [7, 43] in terms of the following three points. First, we took inspiration from bioluminescence and showed that LED lights that simulate communication cues used by living creatures may have analogous effects on human perception and psychological functioning. Second, we proved that findings from color science and color psychology can be referred to as theoretical groundings by HRI researchers to design effective light expressions. Third, we tested a large design space that contained 44 candidate light expression combinations from a possibility of four colors, six patterns, and two levels of intensity. This allowed us to observe common trends for the effects of the features of expressive lights (color, pattern, and intensity) regarding two perceptions: attractiveness and hostility. To summarize, our findings suggest that there are potential effects of expressive lights on influencing people's perception and behavior, therefore we intend to delve further into the exploration of the use of expressive lights in HRI.

On the basis of the results, we offer five design guidelines for the design of affective expressive lights:

I. Blue light is recommended to show attractiveness in a robot;
II. Red light is recommended to show hostility in a robot;
III. Patterns such as split and circle can be attractive to humans;
IV. A low intensity (frequency) can be used to support the expression of attractiveness, while a high one can be used to support the expression of hostility;
V. With regard to expressing strong or weak emotions, the type of waveform, e.g. rectangular or sinusoidal, is less important compared with color and intensity.

6.1 Limitations and Future Work

Several limitations of this work should be recognized. First of all, the effects of expressive lights on human behavior (in practical HRI contexts) remain purely potential as we did not explicitly investigate dynamic human interaction behavior. In this study, we employed a video-based HRI method because such a crowd-sourcing-based approach enabled us to access a large and diverse set of participants. Compared with a live HRI method, previous studies (e.g., [45]) have shown that a video-based method can provide comparable results in certain contexts, such as when a robot approaches a person (similar contexts are used in this work). However, people's perception and especially their behavior would possibly differ in contexts where s/he were a participant of an interaction or were simply an onlooker. Therefore, future work needs to apply live HRI to reveal direct evidence for the influence of expressive lights on human behavior.

It should also be noted that the results of the first experiment seemed to have fairly small effect sizes. With regard to the analyses of both attractive and hostile perceptions, the majority of ratings were given within the range of two to four. Therefore, the fact that the effect on people was not so large means that this work may not be able to support strong recommendations for using the four expressive lights. However, since both the trends observed in the first experiment and the results of the validation study support our findings, we consider our proposed general design guidelines to be valid and useful.

Besides, due to the fact that color carries different meanings in different contexts [21], the generality of this work may be limited. Therefore, research on expressive lights needs to be explored with various HRI contexts. Moreover, since the effects of color on humans may depend on culture (in particular cases, for example, red has positive meanings in Chinese culture) [21], it is also of importance to test our findings (obtained with Japanese participants) on people with different cultural backgrounds.

This work can be further explored. We decided upon our 44 candidate expressive light patterns by referring to color psychology theories and bioluminescent light patterns in nature. Different design approaches (e.g., [32, 33, 42, 44]) can be applied to the early design stage to guarantee that a set of highly representative candidate light patterns are prepared for the later experiments and analysis. With regard to evaluation, interaction attributes [32, 33], as a set of vocabulary for describing interaction experience, may be useful for investigating people's subjective experience of perceiving and interacting with the robot. We also suggest applying constructed scales rather than single terms (attractiveness and hostility) to investigate people's perception. In addition, future work is required to investigate more design factors (e.g., a robot's shape and arrangement of LEDs). Results from such studies would provide further insights and be more generalized to various types of robots.

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