Enhancing Human Understanding of a Mobile Robot's State and Actions using Expressive Lights

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Abstract— In order to be successfully integrated into human-populated environments, mobile robots need to express relevant information about their state to the outside world. In particular, animated lights are a promising way to express hidden robot state information such that it is visible at a distance. In this work, we present an online study to evaluate the effect of robot communication through expressive lights on people's understanding of the robot's state and actions. In our study, we use the CoBot mobile service robot with our light interface, designed to express relevant robot information to humans. We evaluate three designed light animations on three corresponding scenarios for each, for a total of nine scenarios. Our results suggest that expressive lights can play a significant role in helping people accurately hypothesize about a mobile robot's state and actions from afar when minimal contextual clues are present. We conclude that lights could be generally used as an effective non-verbal communication modality for mobile robots in the absence of, or as a complement to, other modalities.

I. INTRODUCTION

Mobile robots are entering our daily lives and are expected to carry out tasks with and around humans in environments such as hospitals, supermarkets, hotels, offices, and shops. For effective operation of these robots, it is important that humans have an understanding of some of the processes, states, and actions taking place on the robot pertaining to the tasks performed and to the robot itself. Verbal communication combined with on-screen display is the typical communication mechanism for communicating with humans. However, for autonomous mobile robots in human environments, humans are not always in close proximity to the robot and these communication mechanisms may fail.

Dynamic visual cues [1], and more specifically dynamic lighting [2], have been shown to elicit interactive social responses. These results potentially suggest that *expressive lights* on a robot are likely to create more engaging interactions with humans. These persistent lights might also serve as a complement to existing modalities of interaction which are often transient (e.g., speech) or that require close proximity (e.g., on-screen text). Moreover, in the work mentioned on dynamic visual cues [1], an important part of the social

response observed was attributed to the fact that the cues expressed a tangible property of the real world (namely the level of interaction in the environment) in an abstracted way. This observation particularly suggests that an abstracted expression of a robot's state through visual lighting cues may also increase social engagement.

We hypothesize that expressive lights on robots would provide an opportunity to communicate information about robots' state at a distance without the verbal or written cues that are typically used. We focus our study on light expressions for three classes of states in which our autonomous mobile service robot, CoBot, typically finds itself: (1) progress through a task with a fixed goal, (2) obstruction by an obstacle, and (3) need for human intervention.

In our prior work, we conducted a design study in which we captured participants' preferences on how a robot should use lights to express an instance of each of these classes of states [3]. We demonstrated participant consensus on a light animation for each of these instances, with specific animation patterns, speeds and colors associated with them.

In this paper, we present our subsequent study to evaluate the effect of these light expressions on people's understanding of the robot's state/actions when viewed at a distance. In the study, we presented online participants with videos of our robot in nine different scenarios related to the three classes of states mentioned above. These videos shot at a distance emulate the viewpoint of a human observing the robot at a distance, where speech and on-screen text would be imperceptible. Half of the participants saw the robot performing with its expressive lights on and half saw the robot performing with the lights off. Our results show that, even though the particular scenario in which the robot is shown affects the accuracy of participants' understanding of the robot, *the presence of lights significantly increases that understanding regardless of the scenario*. We conclude that using expressive lights to symbolically represent robot states is a promising way to intelligibly communicate this information to humans from afar.

II. RELATED WORK

Light signals have been widely used in the history of mankind to convey information at a distance or in low visibility environments, such as in aviation and maritime navigation [4], but these signals often need to be learned. In contrast, personal electronic devices make use of more intuitive, walk-up-and-use light patterns to convey information to the user. We see light indicators on all sorts of devices from cell phones to toasters, and their expressivity can be greatly

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exploited to convey diverse information about the device's operation [5]. Expressive lights have been used as well on apparel [6] and interactive art installations [7] [8]. Stage and scene lighting also share common expressive features with indicator lights like color, intensity and time-varying patterns [9], but there the purpose is to illuminate rather than using the light source itself as an expressive modality.

The use of lights for non-verbal communication on robots remains rudimentary. Most of these uses do not have a direct functional role but rather create abstract impressions (such as "artificial subtle expressions" [10]), express emotions [11], or serve as very basic indicators (e.g., battery level). To the best of our knowledge, the only instances of functional light communication in robots are for human-robot speech synchronization [12] and for communicating intent in robot navigation [13]. In [12], an animated LED is used to avoid utterance collisions in verbal human-robot communication by making it subtly blinking between the user's speech end and the robot's speech start. In [13], a LED array is used to communicate direction of navigation on a quadcopter. This last work fits our idea of expressing robot state information through light animations. However, in the prior work, the expressed feature (directionality) remains a low-level one and the light expression has little abstraction to it.

In contrast, we focus on higher-level, task-related features of the robot's state. To map such high-level features to appropriate light expressions, we first needed to understand what animation parameters would accurately represent such abstract concepts. Color theory [14] provides a good starting point for the design of colored light animations carrying meaning (in our case related to robot state). However, it remains difficult to predict the appropriateness of animations for light sources extending in space beyond a single point (e.g., light strips) and expressing meaning in relation to a complex machine such as a robot. In our previous work, we conducted a specialized study to select appropriate designs for robot expression through lights [3], described in the next section. Using our designed animations, in this work we evaluate the effect of the lights on people's understanding of the state and actions of our mobile service robot, CoBot, moving in the real world. We also look at how the effectiveness of our animations generalizes to other scenarios sharing common features with the ones used to design them.

III. Mobile Robot States and Light Expressions

Our autonomous mobile service robot, CoBot, is capable of performing many tasks in the environment [15]. In this section, we describe CoBot's capabilities and discuss opportunities for enhancing the understanding of CoBot's state and actions when viewed at a distance. We present details about our prior work to construct a light animation interface used on CoBot which helps to express robot states [3].

A. Overview of CoBot and Its Tasks

CoBot can perform a set of tasks for humans in a building across multiple floors. Building locations (offices, kitchens, and elevators), as well as the navigation map of the building,
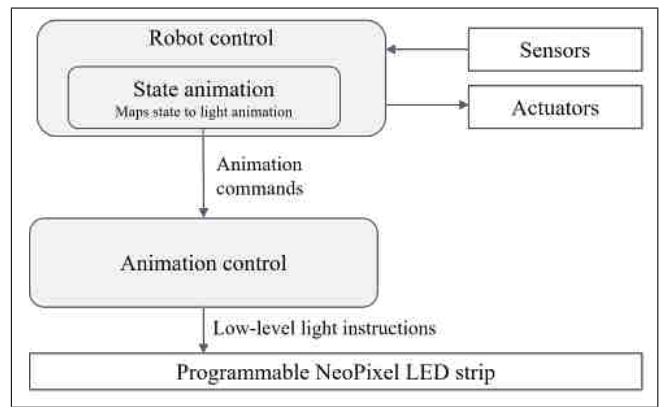

Fig. 1: Diagram of the robot expressive light interface

are known to the robot. CoBot navigates autonomously while avoiding obstacles during its navigation. When facing limitations (such as pressing the button of an elevator or loading/unloading an object on/from the robot), the robot asks for help from humans in the environment [16].

The tasks offered by CoBot are the following:

- **Go-to-Location** task, in which the robot goes from its current position to a goal location.
- **Item transport** task, in which the robot transports an item in its basket from a start location to a goal location.
- **Escort** task, in which the robot accompanies a person from the elevator to a goal location.

When CoBot is moving, it is difficult to discern how much progress it has completed in its task. Similarly, when CoBot is stopped, it can be difficult to discern from a distance whether the robot is stopped for its task, whether an obstacle is blocking its path, or whether it requires help from a human. Expressive lights are one way in which CoBot can help clarify its state to humans in the environment.

B. Expressive Light Interface

For our robot's light interface, we used a programmable, fully addressable NeoPixel LED strip[1] with 91 pixels interfaced to the robot's software through an Arduino microcontroller. The light interface architecture is summarized in Figure 1. A module in CoBot's software translates robot state information into light animation parameters and sends them to the Arduino which performs the hardware-specific light control instructions. Examples of light animations for different scenarios are shown in Figure 2. Our Arduino code[2] is not platform-dependent and is compatible with any robot/device capable of serial USB communication.

C. Light Expression Design

The aim of our prior study presented in [3] was to gather "expert" advice about appropriate light animations that could express CoBot's state. Participants were people knowledgeable in one of the following areas: engineering, design, or visual arts. They were provided with information

[1] https://www.adafruit.com/products/1507
[2] https://github.com/kobotics/LED-animation

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(a) Green progress light on an escort task

(b) Flashing red light for path obstructions
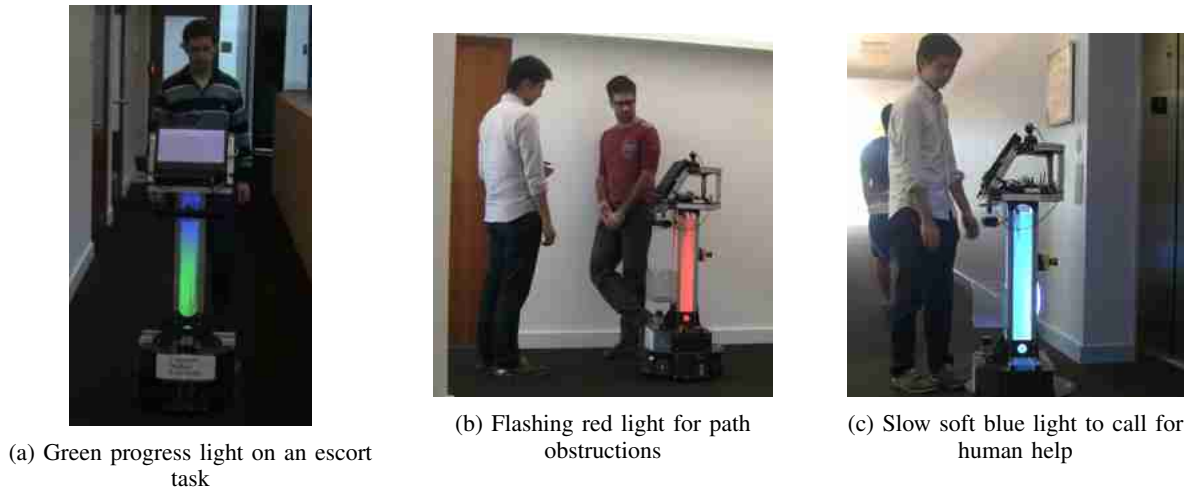
(c) Slow soft blue light to call for human help

Fig. 2: Examples of CoBot light animations in different scenarios

about CoBot and its tasks, and were asked how they would demonstrate the following using expressive lights:

- *Progressing to a goal*: CoBot shows its progress on a visitor escort task towards a goal location.
- *Blocked by an obstacle*: CoBot indicates that its path is blocked during task execution.
- *Waiting for human help*: CoBot indicates that it needs human help to press the elevator button.

Participants were asked to vote for the best choice of animation parameters along the following three dimensions for each scenario: (1) animation pattern, (2) speed, and (3) color. For each scenario, the choices presented as videos consisted of three animation patterns, three animation speeds and six colors. Our results showed that participants were consistent in their choices, generally strongly preferring one of the proposed options along each dimension (or two for the color choices). The winning animations, also used in the study of this paper and generalized to more diverse scenarios, are summarized below and depicted in Figure 2.

- "Progressing" animation: a bottom-up progress bar showing the completed distance traveled as a growing portion of the strip lit in bright green.
- "Blocked" animation: a fast red asymmetric fade in / fade out pattern on the whole strip.
- "Waiting" animation: a soft blue slow fade in / fade out pattern on the whole strip.

Note that this study did not control for color blindness (particularly red/green). Though none of the color choices included both red and green in the same animation, the animations should be tested on this population. While this prior study showed consistent results in how an "expert" would design the light animations, in the remainder of the paper we present a study to test those animations on people viewing the robot from afar during a variety of tasks.

IV. STUDY ON THE EFFECT OF LIGHT EXPRESSIONS

In order to evaluate the effectiveness of the chosen expressive light animations, we conducted an online survey

in which participants watched videos of a robot performing tasks from afar. At the end of each video, participants were asked to hypothesize about the robot's current *state*, but also about its *actions* (i.e., reasons for performing a specific action such as stopping or being unresponsive). Questions were in a multiple choice format, with four possible answers. Half of the participants saw the robot performing tasks with its expressive lights on ("Lights on" condition), and the other half saw the robot without its expressive lights off ("Lights off" condition). Participants were randomly assigned to one of the two conditions. We analyzed participants' hypothesis choices to demonstrate that those who saw the robot with the lights on were more accurate and gained a higher level of trust in robots from watching the videos.

A. Participants

A total of 42 participants (recruited through email and online advertising), of which 14 were male and 28 were female, took part in the study. Ages ranged from 20 to 67 ($M = 32.4$, $SD = 13.7$). Out of the 42 participants, 33 live in the United States; the rest live in different countries across Asia and Europe. Even though computer usage was relatively high amongst participants (31 out of 42 used computers 30+ hours per week), experience with robots was generally low. Only 5 out of the 42 participants reported having worked with robots before, and 20 reported that they have never seen a robot in person before (3 participants had seen our particular robot, CoBot, before taking the survey). Finally, we ensured that none of the participants were colorblind, since our light animations included color and it could have an effect on our results.

B. Survey Design

Our online video-based survey comprised nine video scenarios of CoBot acting in our environment followed by a multiple choice question asking participants to choose a hypothesis aboutwhat the robot was doing. Four plausible hypotheses about the robot's state/actions were presented as choices for each video, of which one had to be selected. The

TABLE I: Scenarios used in the study

Scenario class	Progressing to a goal (P)	Blocked (B)	Waiting for human input (W)
Scenario 1	Navigation task with human presence (P1)	Human obstacle facing the robot (B1)	Symbiotic autonomy (elevator button) (W1)
Scenario 2	Speech task (P2)	Human obstacles looking away from the robot (B2)	Object loading (W2)
Scenario 3	Battery charging (P3)	Non-human obstacle (B3)	Confirming task completion (W3)

video order, as well as the choices for each answer, were randomized to avoid any order effects.

Each of the video scenarios was recorded using our autonomous robot with lights on and lights off. Although the robot was acting autonomously, the videos were replicated as close as possible for the two conditions. We can reasonably assume that the only notable difference between the two videos for a given scenario is the presence or absence of lights on the robot. The videos did not include any robot speech or any visible information on the robot's screen.

After viewing all nine videos, some relevant background and related information, including trust questions about this particular robot and robots in general, was also collected. A copy of the full survey can be accessed online[3].

C. Scenario Descriptions

The nine scenarios shown in the videos were specifically chosen based on actual tasks that the robot performs while it is deployed in our buildings. We focused our scenarios on the same three common *scenario classes* studied in our prior work – "progressing to a goal", "blocked", and "waiting for human input". For each scenario class, we produced three distinct scenarios in which the robot's state or actions are ambiguous, which are summarized in Table I and described below.

The **"progressing to a goal"** scenarios represent the robot taking actions for a long duration. For each of these scenarios, the progression was modeled as the light expression of a progress bar (see section III-C). The scenarios chosen in this class are:

- *Navigation task with human presence (P1)*: A person is being escorted by the robot to a goal location. When present, the lights show the progress on the distance traveled.
- *Speech task (P2)*: The person asks a question to the robot, which provides no immediate answer, as it is searching the web for the required information. The video ends before the robot responds. When present, the lights show the progress on the web query task.
- *Charging (P3)*: The robot is charging inside the laboratory (the video doesn't show the power plug). When present, the lights show the battery level increasing progressively (video sped up 10 times).

The **"blocked"** scenarios represent the robot being interrupted in its navigation by obstacles of different kinds.

The blockage is supported by the fast red flashing light (see section III-C). The scenarios chosen in this class are:

- *Human obstacle facing the robot (B1)*: The robot is blocked in its navigation by a person standing in a narrow corridor, facing the robot.
- *Human obstacles looking away from the robot (B2)*: The robot is blocked in its navigation by a person standing in a narrow corridor, facing away from the robot.
- *Non-human obstacle (B3)*: The robot, navigating down a narrow corridor, detects a person walking towards it and changes its navigation path to avoid the person. As a result, it finds itself in front of a branch of plant, which it considers as an obstacle, causing it to stop.

The **"waiting for human input"** scenarios represent the stopped robot waiting for different types of human actions to be taken. For each of these scenarios, the robot is waiting patiently as represented by the slow flashing blue light (see section III-C). The scenarios chosen in this class are:

- *Waiting for help at an elevator (W1)*: The robot is stopped in front of the elevator, waiting for someone to press the elevator button and let it in. People are passing by, ignoring the robot's presence.
- *Object loading (W2)*: The robot is stopped in the kitchen area, facing a counter on which we can see a cup of coffee. Next to the counter area, a person is washing the dishes, presumably unaware of the robot's presence.
- *Confirming task completion (W3)*: The robot is stopped in front of an office door, with coffee in its basket. A person shows up from inside the office and takes the coffee. The robot doesn't react to the person's action and remains still. The person looks at the robot with a confused look on their face.

For each scenario, when lights are present, the default animation on the robot (when no expression is desired) is a static soft blue color.

D. Multiple Choice Questions

After viewing each video, the participants were given choices to explain the robot's state or actions. As discussed earlier, each of the scenarios can be ambiguous to a person viewing CoBot from afar either because of lack of contextual information or because of mixed signals in the robot's behavior. The corresponding answer choices for each video scenario were specifically chosen to reflect many of the possible hypotheses that could correspond to the robot's behaviors. Given our prior work, we theorize that the light expressions will reduce the uncertainty that people have in

understanding robot's behavior, leading to more accurate answers to our multiple choice questions.

Survey question examples

Scenario B1: *In the video above, why did the robot stop?* (a) The robot recognizes the person, who was expecting it, (b) The robot sees the person as an obstacle, (c) The robot needs help from the person, (d) The robot is inviting the person to use its services. (Scenario B1)

Scenario W3: *In the video above, why is the robot not moving after the person has taken the coffee?* (a) It is waiting for the person to confirm the task is over, (b) It has nothing to do, (c) It is low on battery, (d) It is trying to get inside the room but the door is too narrow.

V. RESULTS

Responses to the survey multiple choice questions in the nine scenarios were coded in a binary fashion – three answers were coded as wrong and one answer was coded as the correct answer. The resulting dependent variable *accuracy* was modeled as binary categorical. Additionally, we coded the responses to our questions about robot *trust* (5-point Likert scale). We analyzed the effects of our independent variables – experimental *condition* (binary categorical variable "Lights on" and "Lights off") and *scenario* (nine categories) – on the dependent variables. While our scenarios had a range of difficulty resulting in a range of accuracies, our light animations have a statistically significant effect across all scenarios on participant's accuracy. The participants who saw the robots with lights on also indicated an increase in their overall trust in robots more than those who saw the robot with lights off. Detailed results are presented next.

A. Participant Accuracy

In order to analyze our categorical dependent variable *accuracy*, we used a McNemar's chi-square test in a combined between- and within-subject design. The "Lights on/off" *condition* is our between-subject variable. All nine video *scenarios* were shown to all participants (therefore a within-subject variable). The *participant* is modeled as a random variable within the model as each person may be more or less accurate in general. The McNemar's chi-square tested whether the participants' answers depend on the presence/absence of lights, video scenario, and/or the interaction effects of both the lights and video scenario together.

Our results indicate that there is a statistically significant difference in the accuracy based on the presence/absence of lights ("Lights on" $M = 75.66\%$, $SD = 18.20$; "Lights off" $M = 56.08\%$, $SD = 19.16$, $\chi^2(1) = 22.34$, $p < 0.0001$). The accuracy was significantly higher for participants who saw the lights. Additionally, there is a statistically significant difference in participants' accuracy based on the video scenario (see Figure 3 for means and standard deviations, $\chi^2(8) = 51.22$, $p < 0.0001$) (i.e., some videos were harder to determine the robot's state/actions than others for each participant). However, there was no statistically significant effect by the interaction of the light condition and the video scenario ($\chi^2(8) = 8.26$, $p = 0.41$), indicating that
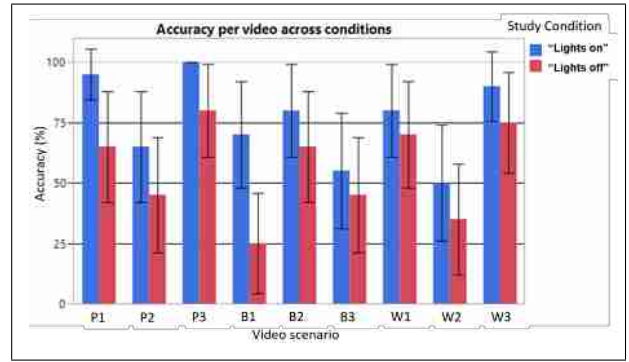

Fig. 3: Comparison of the accuracies on each scenario across the two study conditions with corresponding error bars

the increased effectiveness of the "Lights on" condition was the same across scenarios. Based on these results, we conclude that while the choice of a correct robot state/actions hypothesis does depend on the scenario in which humans see the robot, the tested light animations universally help increase their accuracy.

Figure 3 shows the average accuracy of the participants for each scenario and each light condition. The error bars represent a 95% confidence interval of the mean. We note that the "Lights on" condition accuracies (shown in blue) are universally higher than the "Lights off" accuracies (shown in red). Additionally, the graph clearly shows our result that the video scenarios have different average accuracy, but the accuracy change between conditions per video scenario is not reflective of the scenario.

B. Participant Trust in Robots

On average, participants reported that their trust in robots had increased after watching the videos shown in the survey. (To the question: "Do you agree with the following statement? 'After watching these videos, I will not trust robots as much as I did before.' ", participants in both conditions answered above 3 over 5 on average on a 5-point Likert scale, where 1 meant "Strongly Agree" and 5 meant "Strongly Disagree".) The reported increase in their trust in robots was significantly more pronounced for participants in the "Lights on" condition ($M = 4.29$, $SD = 0.90$) compared to those in the "Lights off" condition ($M = 3.52$, $SD = 0.87$) ($t(40) = 2.02$ two-tailed, $p = 0.008$).

However, there was no statistically significant difference between the two conditions in the reported absolute level of trust in both CoBot and in robots in general ($t(40) = 2.02$ two-tailed, $p > 0.05$), only in the change in trust discussed above did the results differ across conditions.

VI. DISCUSSION

Our results show that our three animations generalize well across several scenarios despite being designed for only a single scenario. Some of our new scenarios (like P3 and W3) even outperform the original scenario. We highlight several aspects of our study design and findings that demonstrate the generalizability of our work to real-world scenarios.

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First, in designing our study, we identified three scenarios that fit each of the classes we had previously studied. The significant effect of scenario on response accuracy shows that some survey questions were harder than others. We can attribute some of the differences to the ambiguity of the scenarios - it is sometimes easier to determine CoBot's state and actions than others. However, it is also possible that the four answer choices we designed were more obvious to choose or eliminate depending on the scenario and the question asked. The fact that the lights universally helped participants distinguish CoBot's state better indicates that the effect of our question choices was relatively low.

Next, in designing our study videos, all of them intentionally lacked obvious contextual clues. Lack of such clues is a usual situation when encountering a mobile robot like CoBot. Visitors often encounter the robot for the first time and interact with it with no knowledge about its capabilities, current state, or expectations from humans. Even for people familiar with CoBot, it is difficult to discern whether CoBot is waiting for help (e.g., at an elevator) or waiting for a new task to perform. In such cases, looking at the robot from afar does not give much insight about the robot's operation, unless other visual cues such as our lights are present.

Since these results rely on the legibility of the animations in the presence of minimal contextual clues, we would expect them to hold for real-world encounters, both at a distance and close-by, as long as the lights are clearly noticeable. In fact, CoBot has been running with its lights for over a year, showing escort progress to visitors, eliciting human obstacles to move away and calling for help at elevators. We have seen noticeable differences in people's behavior around CoBot after adding the lights although as of now we have no quantitative data to assess this behavioral change. It would be useful to measure the impact of these lights in real-world, physical interactions with the robot using measures such as robot waiting time or task completion time.

Furthermore, based on the successful generalization of our three expressions, we hypothesize that such expressions might also generalize to: (1) a broader class of scenarios with similar features; (2) other types of users (participants in this study, having no or limited experience with robots or CoBot, were in some way the "worst case analysis"); (3) other types of robots with similar or comparable domains; (4) other types of light arrays or mounting configurations, as long as the lights are easily noticeable; or even (5) multi-modal interactions in which lights are used in conjunction with speech and on-screen interfaces. In the future, we hope to extract design principles for light expressions in robots which could save design and testing efforts across the aforementioned groups as well as be easily portable to diverse platforms.

VII. Conclusion

We have presented an online study to evaluate the effect of expressive lights on people's understanding of a mobile robot, CoBot, carrying out tasks in an office building. We tested three designed light animations on three corresponding classes of scenarios, for a total of nine scenarios. More than just validating the effectiveness and generalizability of our designed light expressions, our results show that the presence of lights on a mobile robot can significantly help people understand the robot's state and actions. Also, some of our interesting results related to robot trust suggest that meaningful expressive lights could contribute to building more solid relationships between mobile robots and humans.

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