Emotional Expressions of Non-Humanoid Urban Robots: The Role of Contextual Aspects on Interpretations

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ABSTRACT
Self-moving robots may soon be ubiquitous in urban spaces, thereby enabling a wide range of use cases. To increase their social acceptance, previous work has explored how non-humanoid robots can express emotional states through various modalities, such as lights and movement. However, the majority of research has been carried out in controlled lab experiments, raising questions about their ecological validity. In this work, we present the design of emotional expressions for an urban robot via low-resolution lighting patterns and motion cues. We present an in-the-wild evaluation using questionnaires and interviews (N=72). Our findings suggest that a range of contextual aspects can influence the perception of the robot and its emotional expressions, such as overall choreography and interactional context, immediate impact of the environment, coupled with people's own emotions and past experiences. Our analysis thus outlines challenges and provides guidance for designers and researchers working with urban robots.

Author Keywords
Urban robots; low-resolution; emotion; affective computing; human-robot interaction (HRI); urban HRI.

CCS Concepts
•**Human-centered computing → Human computer interaction (HCI);**

INTRODUCTION
Driven by academic and industrial research, robots are increasingly being tested and deployed in urban spaces whether to automate public services, transportation or logistics [33, 49]. Further, researchers have investigated novel pervasive display concepts emerging out of the intrinsic characteristics of urban robots [21], such as mobile urban robots carrying a display, free-floating drone displays [41] or physicalised displays where content is produced by the robot directly manipulating the environment [22]. Yet, if self-moving robots are to become pervasive in the near future, it is crucial that they effectively communicate secondary information to bystanders [5], including internal status and intent (e.g. direction of movement) [34]. Further, similar to domestic robots [17], research has shown that urban robots can provoke social interactions and trigger emotional responses [22]. Assigning emotional cues to robots can thereby increase their social acceptance [4, 28], as humans tend to interact with them as they would with living beings [8].

While early related works in human-robot interaction (HRI) mostly focused on facial cues and gestures [19, 40, 43], researchers recently started to explore other modalities, such as movement [2, 8, 14, 25], light [26, 47], sound [3, 48], and combinations thereof [44, 45]. The latter have the advantage that they can be applied to robots of any physical embodiment, including non-humanoid ones, such as drones [8, 10], utility robots [45] and self-moving pervasive displays [21]. Further, bodily expressions are visible from larger distances [29], which is particularly relevant for technology at a city scale [52]. Previous studies demonstrated that those implicit information cues can successfully encode emotions, with different effects depending on the expressed emotion and modality [45]. However, to our knowledge, all of these studies have been carried out in controlled laboratory environments, often focusing on home or work situations as potential application contexts. It is thus questionable if the results are applicable to robots operating in public (urban) settings [12], which highly differ in terms of spatial design [16] and contextual factors [32], including a wider range of possible situations [11]. Further, interactions between robots and humans in public space are rather short and dynamic [18], with people often busy, surrounded by others, and simply not expecting encountering robots [6]. These are all challenging aspects to simulate in laboratory environments, yet potentially also capable of influencing the perception of expressed emotions.

Contribution Statement
Building on previous work on social robots and affective computing, we present the design and evaluation of emotion cues for an urban ground robot via a low-resolution lighting display and motion cues. Following an iterative process, we first designed the emotional expressions based on related work, and then refined them through insights gained from two expert workshops. By following a mixed-method evaluation approach in a public setting, we ensured participants were not biased by the purpose of the study when first approaching the robot. We then identified contextual and aesthetic aspects - such as interactional context, environmental lighting, or the shape of the robot itself - also influencing the interpretation of emotional expressions. Discussing our findings, we aim to support designers and researchers by providing a starting point towards a better understanding of the impact of context in the perception and acceptance of urban robots.

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Figure 1. Chalk-drawing robot Woodie deployed as an urban probe at an outdoor lighting festival.

RESEARCH CONTEXT: URBAN ROBOTS AS AGENTS FOR PHYSICALISED DISPLAYS

This study has been carried out in the context of a larger research project, which explores the application of urban robots to create physicalised public displays. It builds on previous work using non-digital transient approaches for displaying information (e.g. chalk), which provide several benefits, such as ad-hoc deployment and ability for direct manipulation of content [27, 31]. The research investigates the use of urban robots for automating and scaling-up physicalised displays, while at the same time the robot acts as facilitator for participatory and creative placemaking. The design and deployment of the chalk-drawing robot, named Woodie, was previously described in [22]. This section provides an overview of the research prototype as well as preliminary findings from an initial deployment study, serving as the technological foundation and motivation for the study reported in the later sections.

Research Prototype

Woodie is a self-moving robot which can draw with a conventional chalk stick on the ground, using the public space as a large horizontal canvas (see Figure 1). Measuring approx. 60 centimetres in diameter, the robot is slightly larger than increasingly popular home cleaning robots, such as Roomba, taking into account the scale of the built environment, while still entailing similarities with a familiar object. Woodie's appearance is dominated by its round-shaped 4x16 pixel low-resolution (low-res) lighting display, which is integrated to its polypropylene outer shell. Woodie is built on top of an off-the-shelf robotic platform with four omni wheels powered by stepper motors, allowing precise control over the robot's movement. Woodie is powered by a 12 voltage / 12Ah Lithium rechargeable battery. Its core unit is a Raspberry Pi3, running a Java-based software which sends gcode-commands to the stepper motors conntected to an Arduino board, and controls the WS2812B 5V RGB LEDs of the low-res lighting display.

Initial Deployment Study

To investigate the aforementioned research aims (i.e. scaling up physicalised displays; robot as placemaking facilitator), Woodie was deployed for three weeks in a quiet laneway in the context of an outdoor lighting festival. In order to create precise drawings and not compromise the free movement of pedestrians, the robot itself was moving at a slow speed (0.05m/s). At this stage, the motion was constant without any attempt to encode affective expressions. The low-res interface displayed simple, dynamic light patterns (e.g. a gradient horizontally traversing the circular display) in various colours matching the robot's various states (e.g. moving, drawing), overlaid by a simple vertical marker to visualise the direction of movement. Despite the absence of any intended emotion encoding, or feedback on human's presence and behaviour, the analysis based on observations and on-site interviews revealed that people had an emotional response towards the robot:

- Woodie was often referred to as "something cute", akin to "living organisms" such as a "mushroom" or a "jellyfish".
- People speculated about gender and character traits, e.g. asking whether Woodie was "male or female", or "serious".
- Often we observed smaller children running towards the robot, as if they were chasing animals in public space (see Figure 1). Sometimes children would also go a step further and - mostly (but not always) gently - kick the robot, with one boy later apologising for doing it.

In alignment with Cauchard et al.'s observations for drones [7], the preliminary findings confirmed that people perceived and treated the robot similarly to a living being. This was mainly triggered by the robot's movement, and emphasised by the shape of the outer shell coupled with the lighting patterns. Considering this initial design as a starting point, we aimed to investigate whether an intentional encoding of emotional expressions through movement and light could be successfully related to certain emotions. Further, the interaction and behaviour of people towards the urban robot, such as chasing, kicking and apologising, stressed the need for meaningful communication with people around it in order to promote or discourage certain patterns of behaviour.

RELATED WORK

Previous work in the field of visual perception found that humans can perceive animacy even from single moving objects [50]. This has been considered as a promising finding in HRI [20], in particular for the application of faceless, non-humanoid robots [19, 40], and motivated a series of studies on how to encode robot's emotions through expressive motion cues [2, 8, 14, 25]. Also a range of other modalities, such as light [47, 14], vibration and sound [44] has been explored. In the following, we provide an overview of emotional expression studies in HRI (see Figure 2), narrowed down to those which used movement and/or light, and that were implemented on mobile (aerial / ground) robotic platforms that could be deployed in public space, similar to our research prototype.

Emotion Encoding Through Movement & Light

Conducting a study with a Roomba robot, Saerbeck and Bartneck found a strong relationship between the motion characteristics, namely acceleration and curvature, and the attribution of affect (i.e. valence, arousal and dominance) [39]. Embgen et al. [14] used a mildly humanised mobile robot and found that movement and body poses can successfully encode the basic emotional states defined by Ekman [13]. Angel-Fernandez et al. studied the expressive motion with a non bio-inspired platform [2]. They found that emotional states can be expressed through changes in angular and linear velocity of the robot's movement, whereas changes in the body shape can increase

Study	Impl. Expressions	Modality / Impl. Parameters	Approach
Saerbeck, [39] 2011	Dimensions: valence, arousal, dominance	Curvature + acceleration	L E
Terada, [47] 2012	Anger, surpise, disgust, sadness, joy, fear, anticipation	Hardware (HW): 70 uniformly contr. RGB LEDs Encoding (ENC): colour hue + period of blinking + waveform (smoothness of change)	L E
Embgen, [14] 2012	Happiness, sadness, fear, curiosity, embarrassment, disappoitnment	Head posed and ear poses HW: Single RGB LED + pointing laser ENC: colour hue (LED) + movement (laser)	L E
Sharma, [42] 2013	Dimensions: valence, arousel	The Laban Effort System: space, weight, time and flow	L E
Knight, [25] 2014	Happy, sad, confident, shy, rushed, lackadaisical	The Laban Effort System: space, weight, time and flow	L E
Angel-Fernandez, [2] 2016	Anger, disgust, sadness, happiness, fear, neutral, curiosity, embarrassment	Speed + linear velocity + angular vel. + direction + orientation towards person	L E
Cauchard, [8] 2016	Personality traits: Exhausted, Anti-Social, Adventurer	Speed + reaction time + altitude + special movement	F E
Song, [45] 2018	Anger, surpise, disgust, sadness, happiness, fear, calm	In-situ motion: pattern (turning vs shake) + speed HW: 60 uniformly contr. RGB LED strip ENC: colour hue + period of blinking + waveform	L E

Legend: Ground Robot, Aerial Vehicle, Human-like, Non Human-like, Light, Movement, L Lab Study, F Field Study, E Experimental Study

Figure 2. Overview of related emotional expression studies in HRI.

the identification rate. While these studies applied ordinary movement parameters, others designed the motion cues based on the Laban Effort System, which includes the four vectors of time, weight, space and flow [25, 42].

Work in social psychology demonstrated the effects of colours on emotion [51]. As dynamic lighting comes with a rich set of parameters to encode information [30] and different moods [23], LED based displays have also been explored in the context of HRI: for example, Terada et al. studied how colour and changes in luminosity can convey emotions, and found a relationship between hue value and basic types of emotion, whereas duration and waveform of temporal changes can encode the emotion intensity [47]. Song et al. investigated the effectiveness of expressive lights, in-situ motions and their combination to express seven emotions [44]. The result suggests that the combination of in-situ motions with expressive lights was more effective than using a single modality. Therefore, we decided not to study the effect of lights and motions separately, and instead build on this promising combination.

Evaluation Approaches

As illustrated in Figure 2, all of the previous studies matching our selection criteria followed an experimental research approach, and apart from the study by Cauchard et al. on drones [8], all of them have been conducted in a lab environment. However, findings across various disciplines indicate that 'context' might play a crucial role when it comes to the perception and acceptance of urban robots: for example, research on visual perception suggests that the spatio-temporal context significantly influences the perception of animacy, which is stronger in dynamic contexts [36]. Through a sociotechnical lens, Vande Moere and Wouters identified contextual characteristics of large-scale pervasive displays impacting its successful integration to the social and urban fabric [32]. Regarding those findings, and considering urban robots as an emerging form of pervasive urban displays [15, 21], we therefore think it is important to evaluate HRI - similar to public displays - beyond the lab [1] to understand robots in context.

METHODOLOGY

Emotional Model

There are two main psychological models on emotion recognition that are widely adopted for social robotic applications [9] (see Figure 2): Russell's Circumplex Model of Affect [38], which characterises emotions in a circular space of two dimensions, namely valence (i.e. positive or negative connotation of the emotional state) and arousal (i.e. intensity of the emotion). The second one is defined by Ekman and Friesen, which classifies emotional expressions into six basic emotions, including anger, disgust, fear, happiness, sadness and surprise [13]. In this study, we adopted the latter because a) these six emotions are essential emotions of human-beings across different cultures, which would also be essential for an intuitive human-robot interaction and b) the model is widely used by studies in the field of artificial emotions [9].

Design Concepts

We designed the light patterns and motion cues for the six emotional expressions (see Figure 3) based on the previously presented literature review, and additional related research on colour perception and low-resolution lighting displays. While the previous implementations that used expressive lighting to convey emotions were limited to either a single-coloured LED point light [26], a set of non-individually controlled LEDs [47], or single-row LED strips [45], our research prototype features a slightly higher spatial resolution. This allowed us to incorporate simple pictorial elements in the design, rather than solely relying on basic parameters, such as colour, period or waveform. Our approach was as follows: in a first step, we designed static colour patterns, with colour sets derived from a previous study in which designers were asked to match the six basic emotions with a set of three colours [37]. We then added simple animation effects using Java-based Processing, e.g. to express disgust, we chose to blur and fade green and yellow colours to symbolise a "disgusting liquid". The animation speed, or change in luminosity respectively, was designed according to the dynamic parameters by Terada et al. [47]. For the initial design of motion cues, we created trajectories according to Saerbeck et al. [39], and the speed level with reference to Song et al. [45] and Angel-Fernandez et al. [2].

After creating an initial set of expressions, we conducted two design workshops, each lasting for one hour: the first with a senior researcher in human-computer interaction and two design students, and the second with two senior researchers in robotics, a PhD student in design and a graduate interaction designer. The aim of these workshops was to evaluate the initial candidate expressions with experts, and adapt the expressions accordingly based on their feedback. We first presented the designed light patterns on the actual prototype and asked for their comments in an open discussion round. Next, we asked participants to draw trajectories with the according speed levels (high, medium, low) on a piece of paper, before presenting and discussing our initial motion cues together with the light patterns. Based on a thematic analysis of the workshops, we iterated all expressions apart from happiness. For example, for the anger expression, the participants mentioned that the initial design (see Figure 3, bottom) looked rather "like a machine

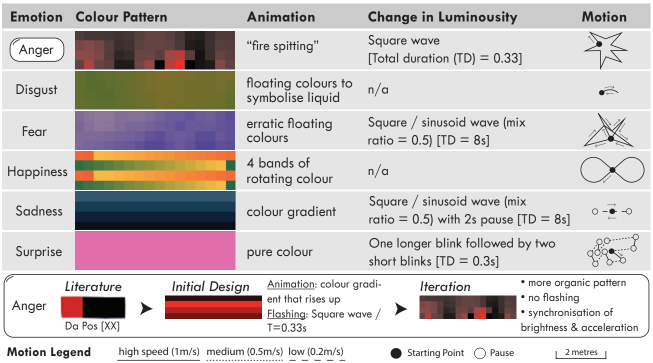

Figure 3. Overview table of the final emotional expressions (top), exemplified design iteration for anger expression (bottom).

reporting a technical issue". They stated that the intensive flashing might make people anxious and uncomfortable, rather than representing the internal emotional state of the robot. Although the trajectory drawings made by participants differed from each other, their chosen speed parameters were mostly conform with previous literature and our initial design considerations. Also, some reoccurring patterns could be identified, for example happiness was often represented through symmetric and round-shaped paths, whereas anger and fear through more erratic paths.

In-the-wild evaluation

Location Description & Deployment Duration

We conducted the field study in a pedestrianised area of an university campus (see Figure 4), which leads to the university's main building. The walkway is open to the general public and connects two nearby suburbs, which is why it is usually very busy and therefore a good representation of an urbanised area. With approximately 150 metres in length and 15 metres in width, the walkway provides enough space for the robot to move, while not becoming an obstacle for pedestrians. The field study was conducted on four weekdays in two consecutive weeks, i.e. Tuesday (1x), Wednesday (1x), Thursday (2x), in order to ensure that the urban situations were comparable. We started with the deployment of the robot shortly after sunset in order to ensure that the lights were noticeable by pedestrians. On each study evening, we kept the robot out for approximately 2.5 hours, adding up to a total of 10 hours.

Procedure & Participants

After deploying the robot on the walkway, we set up one of the six implemented emotions by the means of an iPad. After selecting an emotional expression, no further control was required as both the movement and lighting patterns would play in a loop. While in the initial field study the robot was drawing with chalk, for this study we eliminated this feature, to solely focus on the impact of lighting and movement. To increase the perception of autonomy of the robot and avoid that the initial contact between pedestrians and the robot would be influenced by our presence, we would hide at the entrance of a nearby building. Whenever we spotted someone stopping by the robot, the procedure was as follows: (1) We would approach the person and ask them if they would like to take part in our research study on urban human-robot interaction, however without mentioning the context of artificial emotions. After their consent, we would conduct a short semi-structured interview (see Figure 4, b), asking them about their first impression when seeing the robot and whether they could perceive what the robot was trying to express, however again without mentioning emotions in order to avoid bias. (2) Next, we would inform participants about the research aim of expressing robot's emotions via lighting patterns and motion, handing them a questionnaire. The procedure was adapted from [47], asking participants to rate on a 5-point Likert scale to what extent they agreed that the then currently displayed emotion corresponded to each of the six implemented emotions (presented as an item on the questionnaire). (3) To better understand the reasons for their rating and what influenced their perception of the robot's emotion, we conducted another short semi-structured interview. Both interviews took between three to five minutes each.

Participants who are recruited spontaneously in the wild are usually in a rush. Given our motivation to keep the experience as natural as possible, we decided for a between subjects study design, where each participant would only see one of the six expressed emotions. We first recruited the targeted number of 12 participants per emotional expression, and then set up the robot for the next emotion to be evaluated. Each expression took 1.5 to 2 hours on average. In total, 72 participants (38 female) took part in our study, with age between 20 and 55 years old and thereof 58 participants between 20 and 25 years old. Most participants were academic staff and students, with diverse cultural backgrounds due to the university's large number of international students. As people can either be alone or staying within a group in public spaces, the participants were presented either with an individual (56% of all interviews) or a group interview (max. up to three people), however every participant would fill out their own questionnaire.

FINDINGS & INTERPRETATIONS

Initial encounter with the robot

Passers-by who stopped by the robot usually mentioned that they would have recognised it already from a further distance due to the spaciousness of the deployment location. In most cases their attention was *"attracted by the light"*, followed by the robot's movement. When asking about their perception of the robot, only 2 out of the 72 interviewee's initially related the behaviour of the robot to emotions. These two participants were presented with the expression for anger and sadness respectively, and interpreted the emotion as intended: *"I think it's angry because it's flashing and pacing towards me"* and *"It has the blue colour which represents sadness"*. Rather than being concerned about what the robot was trying to express, a majority of participants first speculated about the function of the robot, such as *"scanning the area"*, *"measuring something"*

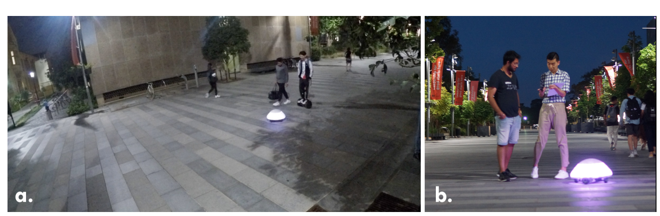

Figure 4. a) The robot deployed on the walkway with two passers-by approaching, b) researcher conducting an interview with a participant.

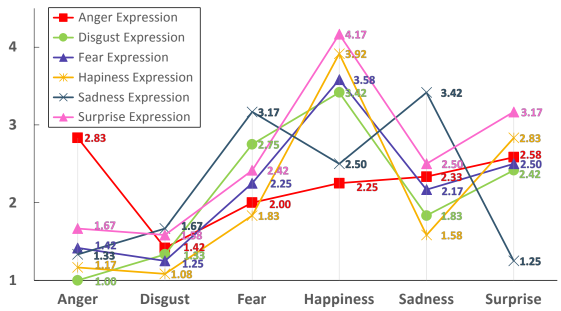

Figure 5. Mean values of the ratings to the six emotions when different emotional expressions were presented.

or *"mapping something on the ground"*, while others felt reminded of the vacuum cleaner *"Roomba"*. Interestingly, in our initial deployment study, where the robot was drawing with chalk on the ground, people did not question the non-utilitarian purpose of the robot, which might imply that people do not expect an embodied robot in public space to fulfil utilitarian purposes per se, however do expect it to somehow manipulate or sense the physical environment. This absence of a primary *"functionality"* led participants to refer to the robot as having a *"decorative purpose"*. Comments were mainly driven by the lighting patterns on the outer shell, which one participant described as *"visually beautiful"*. Independent of the presented emotion, in the initial interview participants would often refer to the shape of the robot as *"cute"* or *"fascinating"*, attributes usually associated to positive emotions.

Perception of the emotional expressions

Figure 5 shows the mean value of ratings for the six emotions when different expressions were presented. The horizontal axis represents the six basic emotions and the vertical axis indicates participants' average ratings. The coloured lines represent data from the presented emotional expression, which we hereafter refer to as expression group. For example, the points on the yellow line belong to the happiness expression group, representing the average ratings of the six basic emotions when the happiness expression was presented. Results show that anger, happiness and sadness were rated the highest in their corresponding groups. These were the expressions with a widely accepted colour cue to match the intended emotion [24], and thus colour was also mentioned as important indicator by participants presented with these expression groups (*"It's sad because it has the blue light which represents sadness"*). It is noticeable that happiness was also the highest rated emotion when the expressions of disgust, fear and surprise were shown. While surprise came second in its own group, fear and disgust were not as well perceived by participants, ranking third and fifth respectively in their groups.

While some patterns in our data are in line with previous work [47], e.g. similarities between emotions (i.e. fear and sadness, happiness and surprise), and difficulty to interpret disgust, there was also a larger variance on how people rated the presented emotions. Therefore, one-way ANOVA only found statistical difference for data from the three expression groups of happiness, sadness and surprise ($p<0.05$). We performed Tukey-Kramer post hoc tests for these three remaining expression groups, analysing how well participants could distinguish the intended emotion from the other five in the group. We identified significant difference between happiness and all other emotions except surprise. For sadness, no significant difference was found between happiness and fear, and for surprise, none was found between happiness, fear and sadness.

Overall, participants perceived the robot's emotional expressions as positive (i.e. expressing happiness). Considering only the parameters we manipulated, participants commented that the *"bright"* colours dominated their perception, but both being too *"joyful"* to express for example disgust or fear. Changes in luminosity and fast movements were also perceived as positive emotions, e.g. *"it's blinking and walking like a little kid"* and *"it's moving around, so I think it's joyful"*.

Contextual aspects

Additionally to the parameters that we manipulated, contextual aspects played a crucial role in how people perceived the robot's emotional expressions.

Spatiotemporal context

The speed of movement was an important indicator for people to interpret the expressed emotion, e.g. *"it looks sad because it's moving slowly"* (✕, ✕)[1]. Moreover, the relationship between movement and its space also influenced people's perception and ability to interpret emotions from it: for example, they concluded that *"[the robot] feels fear because it moves in a very limited space"* (▲, ✳) or *"nervous and lost in the space"* (✕, ●), while another stated that he *"cannot see much from the trajectory because it's very small"* (✳, ✳). Further, the repetition of movement patterns, i.e. the looping of the presented expression, influenced people's interpretation: *"I think [the robot] is sad because it's repeating the same thing over and over again"* (✕, ✳) or *"it's sad because the motion doesn't change"* (✕, ●). Thus we conclude that the overall choreography - which we had not considered in our design and also had not found much attention to in previous work - needs more careful consideration, particularly when it comes to the expression of steady emotional states presented over a longer period of time, instead of singularly triggered by a stimuli.

Interactional context

The movement of the robot towards or away from a target was another factor that people reported as influencing their interpretation of the emotional expression. Fast movement towards themselves or other bystanders was more likely perceived as anger - *"I think it's anger because it's flashing and pacing towards me"* (■, ■) - while movement away was interpreted as fear: *"It feels fear when it moves away, similar to when you are approaching a wild animal and it will step back"* (▲, ▲). Participants who referred to the missing sensing capabilities, were more likely to perceive the movement and light patterns as *"random and erratic"*. Participants commented that *"it would help to read the emotion if it's in response to something"* or *"responsive to themselves"*. This finding is in line with the work from Angel-Fernandez et al., who stated that when an actor played the stimulus to trigger an emotion, people could better perceive the robot's emotional state [2].

[1] read as: (*highest rated emotion of this participant: sadness* ✕, *intended emotional expression: sadness* ✕)

Projection of own feelings

In the post questionnaire interviews, participants often mentioned that their own emotional state would influence the emotion they perceived on the robot, so they would *"reflect [their] own feelings to the robot"* (∗, ▲). One assumed that *"the way we perceive [the robot's] emotion is influenced by our own emotion"* (∗, ●). Two other participants, unable to perceive any specific emotion from the robot, stated that *"it's very subjective and it depends on people's mood and experience"* (none, ∗), respectively that *"[she doesn't] have a very strong emotion right now, so [she] can not perceive any emotion from it"* (none, ∗). Conversely, one person mentioned that *"if [he] would feel sad and under pressure, the robot would freak [him] out"* (★, ★), indicating that the robot's simple presence and behaviour could amplify a negative emotional state.

Role of the environment

Our analysis revealed that there are various factors of the environment that impact people's perception of the emotional expressions, which can be broadly classified into *objective* and *subjective* factors: the former are such that have direct physical or visual impact on the appearance of the robot within its surroundings. For example, the ambient lighting (i.e. nearby streetlights) had an influence on the colour and brightness of the low-res lighting patterns. As the the yellow-to-green colour variation looked more yellowish as in the lab, we increased the brightness on-site, however as a consequence participants mentioned that *"[the lights] are too bright to express disgust"*(∗, ●). Also, the tiled floor and the windy weather on one evening resulted in the robot's shell unintentionally shaking, which was picked up as a cue of the robot *"being nervous and scared"* (▲, ●).

Relating to the *subjective* factors, the way how participants perceived the environment and their feelings towards it had a strong influence on their perception of the robot's emotional expressions. The *"relaxing and peaceful"* (∗, ●) environment on campus led their perception towards a more positive direction, what one participant put as follows: *"I don't feel scared here, why would the robot be?"* (∗, ▲). While the majority of participants perceived *"the large open space on campus as safe, and that's why [they] perceive it as joy"* (∗, ▲), one participant opposed that *"for [him] it's a depressing place and that impacts [his] perception of the robot"* (×, ×). Referring to the disgust expression, one participant stated that *"[she] would need a more disgusting environment which would bring out more sense of disgust to [her]"* (∗, ●). Also participants' cultural background and previous experiences might influence how people perceive robots depending on the location in which it is located: *"I'm from Israel, if I saw there something like this, I will be alert if I can't guess its function"* (∗, ×). In extension of our finding suggesting that people projected their own feelings onto the robot, participants also expressed empathy for the robot in regards of the surrounding environment: *"The cold and windy night makes me feel it's scared"* (▲, ●). The fact only a single robot was deployed, was articulated in the form of a missing sense of belonging: *"I assume it feels fear because there is no one of his kind around"* (▲, ●) and *"I think it's sad because it's only by itself. If there are in a group, I would think it's cute."* (×, ■).

DISCUSSION & CONCLUSION

Our in-the-wild exploration revealed various contextual aspects that influence the perception and interpretation of robots' emotional expressions via low-res lighting patterns and motion cues. While some can be addressed through careful consideration of those aspects during the design of the encoded parameters, others are more complex in nature. For example, the design must consider the spatio-temporal and interactional context: for steady emotional states of positive valence, there should be some variety in the robot's behaviour. While sensing capabilities might further improve expression of emotions, with people acting as a trigger for emotional expressions, this also brings new challenges as robots in public spaces have to deal with multiple users [18]. Both our studies also suggested that the robot's shape impacts people's first impression. Therefore, the shape should support the personality trait of the robot, while shape-changing display technologies might pave the way to amplify sudden emotional expressions [46]. Furthermore, our study suggests that the perception of a robot's emotion depends on highly subjective and intangible factors, such as a) people's own feelings, and b) how they perceive the surrounding environment. Not only designing those is much harder, but their nature may also change overtime once robots become more ubiquitous. That said, designers should still carefully consider the reasons for expressing certain emotions in response to people, particularly negative ones. As one participant put it: *"I don't think it's necessary for the robot to express negative emotions in public spaces"*. Current research on group-based emotions in teams of humans and robots [35] might further provide new insights towards more mutual exchange of emotional expressions.

Further, in alignment with research by Zuckerman et al. on domestic companion robots [53], we conclude that also for urban robots the communication of social cues (e.g. emotion expression) is rather expected as a secondary function, which should be layered on top of a primary function. Future research needs to investigate how the primary function of an urban robot influences the interpretation of emotional expressions. For example, social cues from a driver-less car [5] or a delivery robot might be perceived differently from those of a less utilitarian urban robot as presented here in this paper.

As self-moving robots may soon be ubiquitous in urban spaces, an intuitive and natural human-robot interaction is critical to ensure their acceptance. Building on previous research, in this work we presented the design and in-the-wild evaluation of emotional expressions for an urban robot via low-resolution lighting patterns and motion cues. To our knowledge, this is the first study on robot's emotional expressions in a real-world urban context. With regard to voices in the HRI community urging members to carry out more research in the wild [12], while also perceiving an increasing interest in the pervasive display community towards self-moving robotic displays [21], we hope that our findings are equally valuable to researchers of both communities, while at the same time highlighting the synergies between both areas of research.

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