Designing an Expressive Head For a Help Requesting Socially Assistive Robot *

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Abstract. In this paper, we present the developments regarding an expressive robot head for our socially assistive mobile robot *HERA*, which among other things is serving as an autonomous delivery system in public buildings. One aspect of that task is contacting and interacting with unconcerned people in order get help when doors are to open or an elevator has to be used. We designed and tested a robot head comprising a pan-tilt unit, 3D-printed shells, animated eyes displayed on two LCD-screens, and three arrays of RGB-LEDs for communicating internal robot states and attracting potential helpers' interest. An online-study was performed to compare variations of eye-expression and LED lighting. Data was extracted from the answers of 139 participants. Statistical analysis showed significant differences in identification performance for our intended eye-expressions, perceived politeness, help intentions, and hedonic user experience.

Keywords: Mechatronic design · Expressive robot head · Social robots

1 Introduction

1.1 Application Scenario

The work presented here is part of the robotic research project *FRAME* (Assisted elevator use and room access for robots by involving helpers) [1], which is dealing with a fundamental problem for socially assistive robots without any manipulators [2]. If the robot has to pass through a closed door or has to ride the elevator, especially in public buildings, it can ask for help from people passing by [3]. The aim of the *FRAME* project is to use several robotic platforms in three different application scenarios. One is an in-house postal delivery system, the second one is a robot for item transportation and measuring air pollutant parameters in a small factory, and the third one is a messenger application in a public hospital.

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1.2 Robot

The robot platform used is a *SCITOS G5* robot by *Metralabs GmbH* named *HERA*. Fig. 1 shows the robot which has a movable base with a differential drive and a swivel caster at the rear. Its battery enables the robot for autonomous operation for about 3 h, after which it can autonomously return to its charging station. For navigation purposes, the robot is equipped with several sensors. It has two SICK laser range scanners at a height of 40 cm covering 360° around the robot. For obstacle avoidance, two *ASUS Xtion* depth cameras are covering the closer environment, and an inertial measurement unit (IMU) is used for supporting the correction of the robot's odometry. For perception of people in its surroundings, the robot has three wide angle RGB-cameras covering the whole panorama as well as a *Kinect 2* RGB-D camera on a pan-tilt unit (PTU). Interaction takes place on a 10" tablet and by means of a projector for visualization of navigation goals and advises. Originally the robot had no explicit head. Only the PTU with the *Kinect 2* sensor looking around was present, and the robot lacked any kind of personality, which could be helpful when it comes to interaction with unknown helpers. Against this background, we were looking for a robotic head, that could be placed on top of the robot platform.

Fig. 1: Robot *HERA* with its sensors, interaction devices and the robot's head.

2 Related Work and Design Decisions

The literature provides results mostly for isolated criteria of single design features and some hints at interaction effects.

Song and Yamada [4] studied colored lights, vibrations, and sounds on a real, but simplistic robot. This served to explore the effects in general, but also to verify the intended effects of their design decisions. As Baraka and Veloso [5] summarize, lights are seldom coupled with the state of a robot, although they are sometimes used to underline emotion. In a series of studies, they consequently showed how lighting patterns can be used to clarify a robot's state.

Bennet and Šabanović [6] report results from a study on minimalist robot facial features for emotion expression. They use the upper and lower outline of the eyes as well as those of the mouth and achieved high accuracy in expression identification. Eyes can be a subtle cue for observation and increase cooperative behavior [7]. They can transport emotions in human-robot interaction [8] and should therefore be present when social interaction is a core part of a robot's task. As Marsh, Ambady, and Kleck [9] found, sad or fearful expressions facilitate approach behaviours in perceivers, which is helpful when asking for a favor. Lee, Šabanović, and Stolterman [10] performed a qualitative study on social robot design. Their participants reported that eyes should not be too far apart and also not be too detailed. Also overly large eyes were reported to be intimidating and to be inducing a feeling of surveillance.

The design of the eye part of the robot's head orients itself on 'in the wild' examples. A more comic-like style was chosen due to results regarding the uncanny valley, that is the lowering of trust and likeability when robots get more human-like, but not enough so. Following the general understanding of the uncanny valley phenomenon, Mathur and Reichling [11] reported that staying on the mechanic-looks side of the so-called mechano-humanness score range can also yield high values for trust and likeability as well as low response times.

Therefore, considering also the trade-off between economic and performance-wise aspects, HERA's head (see Fig. 1) was decided to be aimed at this area of machine-likeness. The range of comparable robot heads is depicted in Fig. 2, which was adapted from Mathur and Reichling [11]. A sad or fearful look was chosen for situations in which the robot needs help. Since our design includes only the eyes (see Sec. 3), expression identification performance will have to be checked again.

3 Implementation of the Robot Head

3.1 Prerequisites and Requirements

The design of the head pursued different goals and considered the following constraints: main reason for having a head is, that it provides the robot some personality. It is meant as a communication device for interacting with people, who can read from the eye contact, that the robot is addressing individual persons when talking. Furthermore, the head is a means for expressing different internal states of the robot. In the first instance, these are global states like normal operation, error state, or the need for help, but it can also transport emotional states during a dialog. A visual feedback signal with synthetic mouth movements helps to associate voice outputs to the robot head, which physically come from the speaker at the robot's center. As a constructional constraint, we had to integrate the comparatively large *Kinect 2* sensor consisting of cameras, infrared boosters, and a microphone array, which must not be covered. This defines a minimum size of the head, while a maximum size and weight is defined by the used *FLIR PTU-E46-17P70T* PTU's performance (max. payload 4.5 kg).

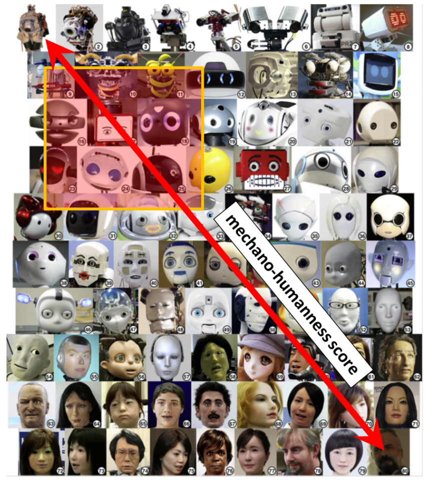

Fig. 2: Robotic heads ordered from machine-like to human-like as compiled by Mathur and Reichling [11] showing the target area of our design.

From earlier projects [12] with a mechanical head, where eye-balls and lids are driven by individual stepper motors and mechanical transmission, we had experiences with failure susceptibility of mechanical components. It took several redesign cycles until the hardware was robust for long term operation. Therefore, the new head design should involve as few mechanical parts as possible restricting us to a display solution, where the eyes are animated. Together with the given minimum width of the head defined by the *Kinect 2* sensor, the size of the front side would be rather huge considering available display formats. This and the positive experiences from the eye design in the SERROGA project [13] led to the idea of using two smaller LCD-displays, each requiring an own HDMI source.

3.2 Hardware

Fig. 1 shows the details of our robot head. Its main structure consists of four 3D-printed parts:

1. a base containing the *Kinect 2* sensor and a mounting plate for the electronics (made from ABS)
2. the back side of the base giving room for the fan and cables (ABS)
3. the glasses which give a frame for the displays and LEDs (translucent PLA)
4. an easy to remove hood covering the inside (ABS)

The shells show organic openings for ventilation and heat dissipation, which makes use of the *Kinect 2*'s built-in fan.

The two 5” touch displays are controlled by two *Raspberry Pi 3 Model B* SoCs which are connected via HDMI and SPI for the touch signal. This allows for a natural reaction when somebody touches the robot into the eye.

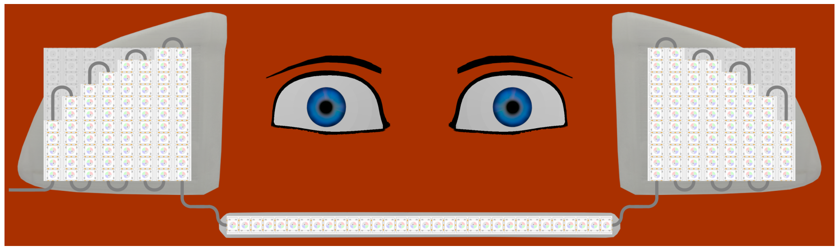

Fig. 3: Wiring of the *WS2812B* LEDs. Greyed out LEDs are not installed but only shown for understanding.

The aforementioned glasses frame (see Fig. 1) is additionally equipped with two arrays of 71 *WS2812B* LEDs on the two sides as shown in Fig. 3. These LED-arrays are intended for expressing the robot's state in order to attract attention. Another 32 *WS2812B* LEDs are arranged as a line in between the cameras and microphones of the *Kinect 2* sensor comprising the robot's mouth. All LEDs are controlled by one of the *Raspberry Pi 3* SoCs.

3.3 Eye Animations and Control

The robot's eyes are realized by means of the *OGRE* 3D engine. Originally designed for computer game graphics, this engine allows for rendering articulated mesh objects and supports weighted superposition of animations for individual objects that can be generated with a 3D animation software like *Blender*. Fig. 4 shows the object structure used for the eyes. Each of the two *Raspberry Pi 3* SoCs renders a frontal orthogonal view of that 3D geometry.

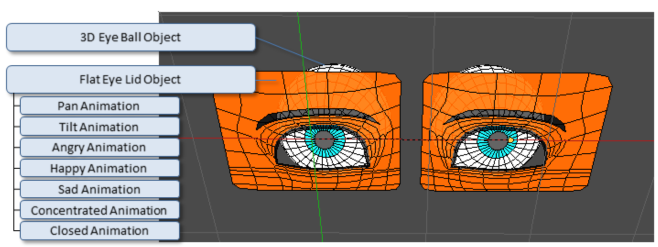

Fig. 4: Structure of the animated mesh for the robot's eyes.

Each eye consists of two 3D objects. One eye ball, that is not animated but can rotate according to the desired gaze direction (important for making eye contact between robot and user), and a flat object comprising the skin with the eye lid and the eye brows. The eye lid object is used for expressing different states but also has to consider the gaze direction and can do an eye blink animation. In the animation software, seven base animations have been defined that have to be combined in real time by means of the *OGRE* engine. The pan and tilt animations cover a movement from left to right and from top to bottom respectively. The emotional expression animation, e.g. angry, happy, sorrow or concentrated (see Fig. 5), contain a transition from a neutral state ($t = 0$) to the fully expressed emotional state ($t = 1$) over the animation's time parameter t (see Fig. 6). The close animation covers the transition from a completely opened to a closed eye.

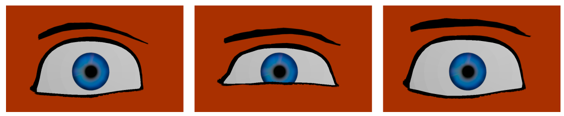

Fig. 5: Normal (left), happy (middle), angry (right) state on the robot's left eye.

For realizing the actual superposition of the base animations, three individual controllers are used in order to define the eye's appearance. Each of the controllers manipulates the time parameter t in the respective animation and provides a mixing weight w in range $[0, 1]$, which defines the influence of the individual animations in the resulting rendering.

Gaze Target Controller This controller gets a 3D position from the application where to look at, specified relative to the robot. Considering the current angles of the PTU, the direction of gaze in head based coordinates can be determined easily, which specifies the desired pan and tilt angle of the eye balls[3].

Furthermore, these angles directly define the parameter t for the pan and tilt animations of the eye lids (position in the animation going from left to right and bottom to upward direction). The mixing weights w for these animations are set proportional to the amount of elongation. Pan and tilt angles close to the angular limits generate weights of 1 overriding the influence of other animations, while angles near zero generate low mixing weights, and therefore, the margin for expressing other animations is higher. The interplay between the direction of the eyes and the head orientation is described below.

Emotion State Controller This is used in order to realize the smooth transition between changing emotional states, which are defined by a five element vector $E = [e_{angry}, e_{curious}, e_{happy}, e_{sorrow}, e_{concentrated}]$ comprising the amount of excitation for each of the emotional states. The application can choose arbitrary combinations of the base emotions and not necessarily has to respect a limit to the speed of change. If the application changes this vector E, the controller slowly approximates the rendered state to it by means of a recursive averaging to avoid jitter (see Fig. 6). The time constant for that is about 0.5 sec.

The E values are directly used as the parameter t of the base animations. The more active an emotion, the closer the animation is to its full articulation. Additionally, the mixing weights w of the animations are activated proportional to the E values. The mixing weights w_{pan} and w_{tilt} for the pan and tilt animation of the eye lid are scaled with $1 - \max_i(e_i)$. Thus, if emotions are activated, the pan and tilt animations are less visible, which prevents from diluting the articulation of strong emotions in case of high gaze direction angles.

[3] Head and eyes movement: `https://youtu.be/PHBMrr7HQzI`

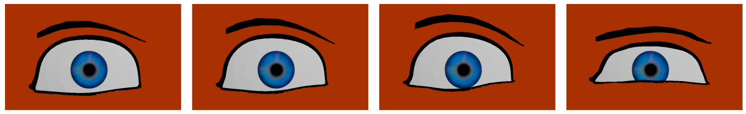

Fig. 6: Morphing between normal and happy state on the robot's left eye. Happy factor (from left to right): 0.0, 0.5, 0.75, 1.0

Blink State Controller This controller is responsible for animating the eye blink events. If triggered, the animation runs continuously from open to closed state and back (t parameter of the animation), while the mixing weights w of all the other base animations are gradually reduced to zero until the closed position is reached. The weight of the closed animation is increased instead. When opening the eyes again, the weights are faded back to the original values, such that the former state is visible again. By means of that, the blink animation can smoothly fade in from arbitrary states and reaches its fully closed position without interference with other emotional states and gazing direction[4].

A last feature of the eye displays is the adaption of external illumination distribution. From the RGB camera in the *Kinect 2* sensor, we get an overall impression of the light sources in the surroundings. The pixels in the RGB image are clustered in order to find color and intensity of the bright spots in the scene around the robot. Since the *OGRE* engine allows to define up to eight point light sources for illumination of the rendered scene, the brightest clusters are used to control the position and color of these lights in the *OGRE* scene. By means of this, it is possible to prevent scary glowing eyes in the dark, while in bright sunlight the contrast is as high as possible.

3.4 LEDs and Control

The three arrays of installed *WS2812B* LEDs as introduced in Sec. 3.2 are handled as three different rectangular matrices internally, simply ignoring missing LEDs (see Fig. 3), which makes it easier to control them. For each of these three groups, five programmable parameters are accessible by the application:

1. light mode
2. color (RGB)
3. speed
4. direction (*UP*, *DOWN*, *FRONT*, *BACK*)
5. mode depending special parameter

The light mode represents the effect the LEDs should show. 14 different modes are available (see Tab. 1). Since the installed *WS2812B* LEDs are RGB, the color parameter accepts a three element vector containing 8-bit values for red, green and blue. The speed gives the cycle speed in Hz, while for asymmetric effects the direction can be specified. The last parameter can control effect-dependent settings like the duty cycle or a line width (see Tab. 1).

[4] Eye emotions and blink: `https://youtu.be/XrsamLVvKO8`

Table 1: Light modes, for visualization see [5]

light mode	description	special parameter
OFF	LEDs off	-
ON	LEDs on	-
BLINK	LEDs blinking	duty cycle $[0, 1]$
PULSE	LEDs pulsing	duty cycle $[0, 1]$
RUNNING	running line	line width
PENDULUM	back-and-forth running line	line width
GROWING	growing line	-
SHRINKING	shrinking line	-
GROWSHRINK	first growing then shrinking line	-
RAINBOW	LEDs show rainbow color	-
RBCYCLE	rainbow running light (red first)	wavelength
RBCYCLE2	rainbow running light (blue first)	wavelength
MATRIX	matrix effect	probability of new dots $[0, 1]$
AUDIO	light line, width controlled by audio signal	audio signal scaling factor

4 Application

4.1 Attention Generation and Status Output

For our application (see Sec. 1), where the robot relies on the help of humans passing by, it is important for it to attract the attention of human helpers. Especially over longer distances, the easiest and most unobtrusive way for attracting attention is a visual stimulus. For this purpose, the robot can make the LEDs in its head light up or flash.

After having attracted the attention of a potential helper, the robot has to communicate with him or her. To unload the voice channel of communication, the color of the LEDs can be used to assist in displaying information about the robot to the helper. This can make it easier to understand the robot's state. Since one of the application scenarios will be in a factory setting, color codes consistent to other machinery should be used. We use the ISO standard *IEC 60204-1* [14] for designing the color design. This standard demands special colors for different machine states (see Tab. 2). Deducing therefrom, the robot has to light the green LEDs when it can do things on its own and the blue LEDs when it needs help. Yellow is also used to warn observers, e.g. when moving through narrow passages. Red is reserved for critical errors and thus not part of normal robot operation.

[5] LED modes and parameters: `https://youtu.be/4WF3vIgE5G4`

Table 2: Meaning of light color according to ISO standard *IEC 60204-1* [14]

light color	meaning
RED	critical error
YELLOW	abnormal state, imminent critical error
GREEN	normal state
BLUE	mandatory action required

4.2 Gaze Following

For being more social, the robot's head and eye gaze should be directed towards the human interaction partner. This can be accomplished coarsely by the installed *FLIR PTU-E46-17P70T* and more finely tuned by the eyes' animation.

When the robot should look towards its human interaction partner, the application provides the 3D position of the human in world coordinates, which results from a multi-modal people tracker, a redesigned and extended version of [15]. The people tracker is integrating detections from laser-based leg detector and image-based people detectors working on the wide angle cameras.

Copying the human gaze, the head should not reflect every small change of the gaze angles. Rather should the head wait until one of the eye gaze angles' change exceeds a threshold and then fully reposition itself to the new gaze direction (for further details on people tracking with a PTU mounted camera see [16]).

In order to realize this behavior, the PTU is using its own controller which implements a hysteresis. The actual eye position then only has to consider the angular difference between the current head position and the gaze target (see Sec. 3.3).

4.3 Simulation of Mouth Movement

Since our application uses an active text-to-speech (TTS) system, the expectations of the interaction partner will be, that the voice goes along with some mouth movement. For this, the mouth LEDs can be used.

The audio stream of the TTS system is processed by a fast fourier algorithm which provides the frequency components of the audio signal to be played. From this power spectrum, a single frequency coefficient (around 440 Hz) is selected and given to the LED controller (see Sec. 3.4), which modulates the width of the mouth light bar accordingly.

5 Study on the Effect of Design Variants on the Perception of Help Requests

A web- and video-based questionnaire was used to compare variations of eye-expressions and LED-lighting for the situation of requesting help as a robot. As Dautenhahn et al. [17] showed, video-based evaluation of robots is feasible, as long as no physical interaction is involved.

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5.1 Materials

Participants were shown video-snippets of the robot asking for help. A total of three variations for the eye-expressions were presented: a neutral, a sad, and a concentrated expression. This subset of expressions was chosen to match the needed states for the planned application of the robot, where it needs to express need for help, being busy and a neutral state. LED-lighting varied between seven levels of color and blink-frequency. The colors shown were blue and green, while the frequencies were 0 Hz, 0.5 Hz and 1 Hz. A control condition with all lights switched off was added as well. LED-lighting was designed as a between-groups measurement while eye-expression was measured within-subjects. After each video-snippet, participants rated the situation they experienced with several questionnaire items. Fig. 7 shows a frame from one of the presented videos.

Fig. 7: A frame with a sad eye-expression from one of the presented videos.

5.2 Measurement

The questionnaire consisted of several items. The first two questions asked the participants to answer, which expression they thought the robot showed and how strong the expression was. Nine alternatives were provided, of which eight were taken from the Facial Expression Identification [6,18]. The ninth alternative was added to include the concentrated expression as well. In addition, the participants could optionally mark one or more further expressions they thought could also be fitting. The second part of the questionnaire consisted of the four items of the hedonic subscale of the short version of the User Experience Questionnaire (S-UEQ) by Schrepp et al. [19]. The S-UEQ consists of a hedonic subscale, which focuses on the pleasantness of an interaction, and a pragmatic subscale, which focuses on subjective performance. The items for the pragmatic subscale were left out to shorten the overall length of the questionnaire, since there was no real interaction happening. The third part of the questionnaire contained two direct questions on the perceived politeness and rudeness of the robot's request as Salem et al. [20] proposed, and one item on how much time the participant would be willing to invest in this situation to help the robot after Pavey et al. [21]. The time had to be input with a unit-less slider anchored at little or much time.

5.3 Results

In the following sections, we first report the results and then interpret them separately. This serves to not mix objective results with subjective interpretation.

During four weeks, a total of 157 participants answered the questionnaire of whom 139 were included in the analysis. Exclusion was based on control items and for one participant on being too young.

Non-parametric tests had to be used, because of the violation of several assumptions for parametric tests. Regarding the initially planned analysis of covariance (ANCOVA), the assumption of homogeneity of regression slopes and the independence of independent variables from the covariates were violated. For the planned fallback analysis with several analyses of variance (ANOVA), severe deviations from homogeneity of variance and from normal distributions were found. Under these circumstances, the stability of type-I errors can not be guaranteed, resulting in inflated false-positives when reporting seemingly significant results. Thus, for the influence of the between-groups LED-lighting variation was analyzed with Kruskal-Wallis-Tests and post-hoc Mann-Whitney-U tests with Bonferroni-correction. The within-group eye-expressions were analyzed with Friedman's ANOVAs with post-hoc Wilcoxon signed-rank tests with Bonferroni-correction.

LED-lighting A Kruskal-Wallis test with the independent variable LED-lighting yielded significant results for help intention with neutral eye-expression ($H(6) = 12.852$, $p = 0.045$) and concentrated eye-expression ($H(6) = 15.891$, $p = 0.014$). Post-hoc Mann-Whitney-U tests with LEDs off as a control group and with corrected significance niveau of $\alpha = 0.008\bar{3}$ were non-significant.

Eye-Expression Friedman's ANOVAs for the three different eye-expressions yielded significant results for hedonic user experience $\chi^2(2) = 10.369$, $p = 0.006$, perceived politeness $\chi^2(2) = 42.792$, $p < 0.001$, facial expression identification $\chi^2(2) = 59.542$, $p < 0.001$ and help intention $\chi^2(2) = 53.043$, $p < 0.001$. Post-hoc Wilcoxon signed-rank tests used a corrected significance level of $\alpha = 0.01\bar{6}$.

For hedonic user experience, a significant difference was found between sad and neutral expression. Significant differences for perceived politeness were found between sad and neutral, as well as between concentrated and sad expressions. For the help intention, there were differences between all levels of eye-expressions. Means and standard errors for help intention, perceived politeness and hedonic UX are depicted in Fig. 8.

The expression identification showed significant differences between sad and neutral, and between concentrated and neutral. The test statistics for all significant post-hoc tests are shown in Tab. 3.

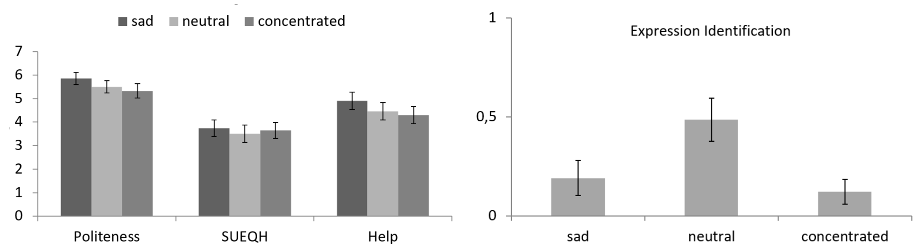

Fig. 8: *left*: Means and standard errors for the effect of eye expression on help intention, perceived politeness and the hedonic subscale of the S-UEQ. *right*: Means and standard errors for the effect of eye expression on expression identification, measured as the share of interpretations consistent with our intended expression.

Table 3: Test statistics of significant post-hoc Wilcoxon signed-rank tests for pairwise comparisons of the eye-expressions sad (S), neutral (N) and concentrated (C).

Dep. Variable	Comparison	T	p	r
Help Intention	S-N	771	< 0.001	-0.319
	S-C	686	< 0.001	-0.397
	N-C	1270	0.005	-0.167
Hedonic UX	S-N	1930.5	< 0.001	-0.222
Perceived Politeness	S-N	623.5	< 0.001	-0.29
	S-C	514.5	< 0.001	-0.337
Expression Identification	S-N	867	< 0.001	-0.331
	N-C	318.5	< 0.001	-0.417

5.4 Discussion of Results

Due to violations of assumptions for parametric tests, non-parametric tests were used as an alternative. The a-priori sample size estimation based on parametric tests thus yielded a much smaller number of required participants than would have been needed for post-hoc tests to find present significant effects. Especially the significant results of the Kruskal-Wallis-H test for variations in LED-lighting could not be confirmed by post-hoc Mann-Whitney-U tests, most probably due to a lack of test power of the latter.

The different eye-expressions differed in how well they were identified by the participants. The neutral expression scored higher in this regard than both the sad and concentrated expressions. This indicates optimization potential for the latter. Tab. 4 highlights how the expressions were interpreted by the participants instead. This knowledge will serve to further refine the respective expressions and to further distinguish them from the non-intended interpretations.

The hedonic UX was significantly higher for the sad eye-expression than for the neutral expression. The sad expression further increased the perceived politeness, compared to both the neutral and the concentrated expressions. Finally, help intention was highest for the sad eye-expression, followed by the neutral and the concentrated expressions. The results confirm and add to the positive effects of sad expressions on onlookers as reported by Marsh et al. [9].

Table 4: Confusion matrix for the tested eye-expressions and answer options. All cells show the percentage of answers for the shown expression in the respective rows. The percentage of replies for the intended expression is underlined. Higher percentages of replies in non-intended categories than in the actually intended category are highlighted in gray.

Shown Expression	**Answer Option**								
	Angry	Happy	Sad	Fearful	Neutral	Surprised	Disgusted	Bored	Concentrated
Sad	1.80	2.88	<u>19.06</u>	32.37	32.73	3.24	0.36	0.72	6.82
Neutral	6.14	3.25	0.72	19.49	<u>48.74</u>	12.64	0.00	1.44	7.58
Concentrated	31.29	2.16	2.16	3.96	42.45	2.88	1.44	1.44	<u>12.23</u>

6 Conclusion

In this paper, we have presented a new design and the technical realization of an expressive robot head, which comprises a PTU, 3D-printed shells, animated eyes displayed on two LCD-screens and three arrays with RGB-LEDs. The display solution and the LED matrix offer various possibilities for adaptation to the respective operating conditions and the interaction states to be conveyed. Therefore, it can easily be used in a conversation to communicate additional information to the dialog partner and to make the experience of interaction more pleasant.

The evaluation of an online study showed, that using the sad eye-expression yields benefits regarding the hedonic UX, perceived politeness, and help intention. Nonetheless, results regarding the expression identification performance suggest that there is further optimization potential for the sad as well as for the concentrated expression. Due to these findings, in future work we will develop more suitable eye animations and test the head in a complex application, where the robot has to navigate in a populated public building requesting help when it has to pass through closed doors or ride the elevator.

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