Gaze by Semi-Virtual Robotic Heads: Effects of Eye and Head Motion

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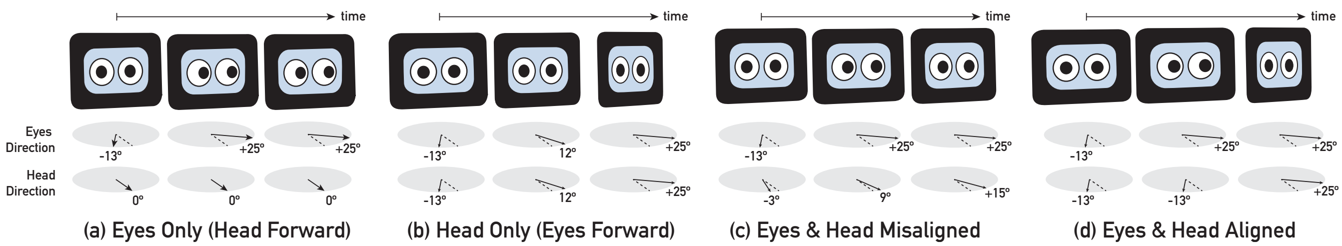

Fig. 1: Sketch of the gaze behaviors that we studied in this work. In each case, the robot gazes from the -13° to the $+25^{\circ}$ direction relative to the robot's forward orientation (identified with dashed lines at 0°). See the text for more details.

Abstract— **We study human perception of gaze rendered by popular semi-virtual robotic heads, which use a screen to render a robot's face. It is known that when these heads are stationary, the screen may induce the Mona Lisa gaze effect, which widens the robot's apparent cone of direct gaze. But how do people perceive gaze when the head can move as well? To study this question, we conducted a laboratory experiment that investigated human perception of robot gaze when a semi-virtual platform looked in different directions. We varied the way in which the robot conveyed gaze, using several behaviors involving 2D eye and head motion. Our results suggest that the interplay between these motions can regulate how wide users perceive the robot's cone of direct gaze. Also, our findings suggest that the location of observers can affect the perception of gaze by semi-virtual robotic heads. We discuss the implications of our findings for social interaction.**

I. INTRODUCTION

Gaze plays an essential role in human-robot communication. By looking in a given direction, robots can signal attention [1], [2], [3] and engagement with users [4]. Gaze can help coordinate turn-taking [5] and facilitates social interactions [6], [7]. Further, robot gaze leads to attributions of agency [1], [8] and can reveal hidden mental states [9], including cognitive effort [10].

We study gaze conveyed by semi-virtual robotic heads. These are common screen-based robotic heads, e.g., such as in Sawyer, Buddy and Misty.[1] For this type of platforms, it is known that 2D eye display can lead to the *Mona Lisa effect* [11] when the head is stationary. This effect biases users perception of gaze, making it seem like the robot has a wider cone of direct gaze than it actually does. This cone corresponds to the range of gaze deviations that an observer accepts as looking directly at them [12], [13].

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[1]More information about these robots can be found in their respective websites: www.rethinkrobotics.com/sawyer, www.buddytherobot.com, and www.mistyrobotics.com.

Can robots with screen faces regulate how wide users perceive their cone of direct gaze? If yes, then they could convey attention through gaze more narrowly or widely as needed depending on the situation. For instance, if they want to address a person in a group interaction, more narrow gaze would be beneficial; but to convey attention to multiple users, a wider cone would help. Interestingly, prior work suggests that such an effect is possible by physically changing the shape of a robot's eyes [14]. In this work, we explore an alternative approach involving different eye and head motion behaviors suitable for semi-virtual robotic heads.

Our work is motivated by prior efforts in Human-Robot Interaction (HRI) that have studied multi-modal mechanisms for robots to convey gaze direction [15], [16], [17]. We contribute to this line of research by conducting a study to evaluate how different gaze behaviors rendered by a semi-virtual robotic head alter gaze perception (Fig. 1). Our results suggest that the interplay between head and 2D eye motion can indeed alter how users perceive the cone of direct gaze of the robot. We discuss the implications of our findings for social human-robot interaction.

II. RELATED WORK

This section describes close related prior work. For general reviews of human gaze and robot gaze, we encourage interested readers to refer to [18], [19] and [20], [21], respectively.

Human Gaze. Humans have become particularly adept at communicating through gaze, developing new pathways and areas of the brain devoted to understanding the gaze of others [22]. However, human gaze perception is not infallible. Humans have a tendency to feel like they are being looked at more frequently than they actually are [23], [24]. For example, in Cranach and Ellgring [23], over 35% of gazes directed outside the face (10 cm from the bridge of the nose) were perceived to be directed at the face given a straight head position. Prior research has also found that head orientation can help clarify gaze direction [25], [26].

Some of the gaze behaviors studied in this work are inspired by primate's eye-head motion patterns. When a primate's head is still, changes in gaze direction are often accomplished with high velocity eye movements [27]. Commonly, the eyes lead head motion when gazing in a given direction [28]. The head's delay is attributed to biomechanical lag due to inertia.

Perception of Robot Gaze. Several factors are known to influence human perception of robot gaze, including a robot's body motion [12], [15], [11], the visibility of its eyes [12], the location of gaze targets [29], and the surroundings [12]. Further, past work has described the emergence of the Mona Lisa effect with 2D face displays [11], [30]. Previous efforts have proposed mechanisms to reduce this effect, e.g., through 3D screens that improve the perception of gaze [31], [32], [33], [11]. Further, past work harnessed the Mona Lisa effect to increase group engagement, because the effect may induce multiple users to perceive as if a robot is looking at them simultaneously [14]. Our work extends this line of research by studying multi-modal gaze by a semi-virtual robotic head.

Computational Gaze. There is a long history of research on rendering artificial gaze. Some efforts have aimed to replicate primates' gaze dynamics, including blinking and gaze aversion patterns [34], [35], [36], [37], [38], [10]. Others have provided new means to convey gaze through 3D off-axis perspective projection [39] or novel physical eye designs [40], [41]. In our work, we use an off-the-shelf screen for rendering a robot's eyes and a simple gaze controller. Our contributions center on understanding at a fundamental level how the interplay between 2D eye gaze and head direction affects gaze perception for semi-virtual robotic heads.

Close to our work, Kawaguchi and colleagues [16] studied the effects of human gaze (shown as still images of a person) on a telepresence robot with a screen face. In their experiment, the robot's face rotation had a relatively small effect on gaze perception. Our work provides new perspectives in this respect as we consider less realistic, cartoonish eyes (Fig. 1).

III. METHOD

We conducted a laboratory study to investigate human perception of robot gaze. Our study was inspired by the experimental protocol from [42], in which five participants repeatedly indicated their perception of the gaze of an agent. In our case though, we ran our experiment with one participant at a time, who evaluated gaze from several locations. This facilitated recruitment and made the environment more controlled, thus reducing potential confounds.

A. Experimental Conditions

As shown in Figure 2, we investigated gaze perception with a modified Widow X arm by Trossen Robotics. The original end effector of the arm was replaced by a screen face, which rendered simple 2D eyes. The eyes were directed towards a desired 3D locations in front of the robot's face using a simplified pinhole projection model. More specifically, a given 3D target $[x\,y\,z]^T$ was converted to pupil positions by first transforming it to a local coordinate frame for each of

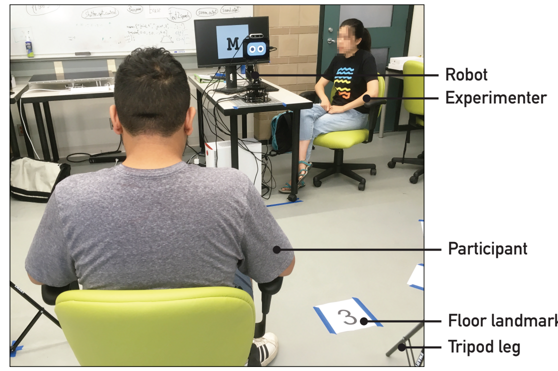

Fig. 2: View of the robot from the perspective of a participant in a pilot session of the study. The participant was seated in Location 2. See the text for more details.

the eyes (e.g., obtaining $[x'\,y'\,z']^T$). Then, the 3D points were projected to 2D: $u = f_x x'/z', v = f_y y'/z'$, with $f_x = 18.8$ and $f_y = 34.3$ based on a calibration procedure similar to [30].

We controlled for the gaze behaviors rendered by the robot, the gaze directions towards which it looked during the study, and the location of the participant who observed robot gaze. In particular, we considered four Gaze Behaviors:[2]

Eyes Only (E). The robot's renders saccades. The pupils of the eyes change position to look towards a desired target while its head stays fixed forward (Fig. 1a).

Head Only (H). The robot's head pans towards a desired target. Its eyes are fixed in a forward looking direction relative to the head. Thus, the eyes always point in the same direction as the robot's head (Fig. 1b).

Eyes & Head Misaligned (EHM). The eyes of the robot look towards the target. Its head stays still, or pans in the same direction of the eyes if the target is 20 deg or more away from the current orientation of the head. But the head does not fully reach the target; it only moves until it reaches 10 deg from the target direction (Fig. 1c). This behavior is inspired by prior work in HRI [43] and human gaze [44].

Eyes & Head Aligned (EHA). The eyes and the head look towards the target. The eyes reach the target immediately, and the head then follows (Fig. 1d). This behavior was motivated by evidence that head orientation can help clarify gaze direction [25].

As in [11], [16], our efforts focused on evaluating gaze perception horizontally because social attention is often communicated along this spatial dimension. Each participant experienced the robot looking towards one set of gaze angles:

Angle Set A. Consists of the angles $\{-25°, -21°, -17°, \ldots, +19°, +23°\}$ relative to the robot's forward direction.

Angle Set B. Consists of $\{-23°, -19°, -15°, \ldots, +21°, +25°\}$. This set was offset by 2° relative to the set A.

The Angle Sets spanned $[-25°, +25°]$ in total. They were devised to keep the length of the study under 1 hour and

[2]The supplementary video shows example Gaze Behaviors.

prevent participant fatigue in comparison to experiencing all directions from $-25°$ to $+25°$.

During the experiment, the robot's face rotated in place above its base and perpendicular to the ground. Head motion from a starting orientation to a new, desired head direction was generated by linearly interpolating with a proportional-integral-derivative controller. The maximum head speed was 400 deg/s. In contrast, the pupils on the robot's eyes moved to a new direction immediately, imitating saccades.

Lastly, we controlled for for the participants location in our study. They sat at a social distance from the robot, according to Hall's proxemics theory [45], and distributed around it as is typical of situated conversations [46]. More specifically, the participants sat at three locations during the study:

Location 1 (L1). The participant was to the side of the robot at $-53°$ from its forward orientation.

Location 2 (L2). The participant was between the Locations 1 and 3, at $-26.5°$ from the robot's forward direction.

Location 3 (L3). The participant was right in front of the robot, seating at $0°$ from its forward direction.

Fig. 3 shows the locations in our study setup. Although people could have also sat at locations 4 and 5, opposite to L2 and L1, they observed the robot only from the 3 aforementioned locations to keep the study under 1 hour and prevent fatigue. This choice was also justified by our study pilots, which provided evidence that gaze perception was symmetric relative to the robot's forward direction (L3).

B. Hypotheses

We had several hypotheses in regards to the robot's Gaze Behaviors and the observer's Location:

H1. The Eyes Only (E) behavior would lead to more gaze perception error and a wider perception of the gaze of the cone of the robot in comparison to H, EHM, and EHA.

H2. The EHM and EHA behaviors would be perceived as more natural by users than H.

H3. Observing the gaze of the robot from its side (Location 1) would lead to more error in the perception of its gaze direction than observing it from in front of it (Location 3).

H1 was motivated by our assumption that a robot's head orientation could help reduce its perceived cone of direct gaze. H2 was based on the fact that people often move both their head and eyes when they gaze in a particular direction [44]. Finally, H3 was a result of initial tests with our robot. We had the impression that observing the robot's face from the side could be more confusing than in front of it.

C. Study Design & Setup

The study had a mixed design. The robot's Gaze Behavior and the participants' Location were run within-subjects, while the Angle Set was between-subjects. We counter-balanced exposure to Gaze Behaviors and Locations with Latin Squares and balanced the number of participants that observed each Angle Set. This resulted in a design in which participants evaluated 13 gaze directions in 12 sessions, one

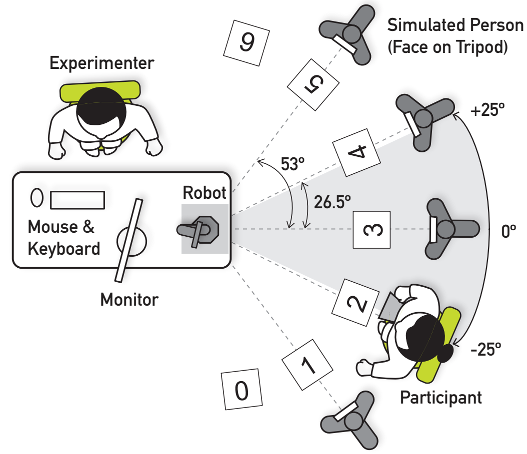

Fig. 3: Experimental setup. The gray cone in ($-25°$, $+25°$) denotes the range of gaze directions rendered by the robot. The participant observed the robot from Locations 1–3.

per combination of Gaze Behavior (4 levels) and Location (3 levels). The order of gaze angles within a session was pseudo-random to prevent ordering effects while ensuring that the differences among Gaze Behaviors were observable.

The study was conducted in a space of 3.5×3.5m. The setup simulated a social interaction between the robot and 5 people (Fig. 3). On the left side, a table was placed for the robot and a computer that controlled it. The experimenter sat behind the robot to start pre-programmed gaze behaviors. Other than that, the experimenter was quiet and looked away from the participant to avoid distractions. On the right, interactants were organized in a semi-circular arrangement. They oriented towards the robot, and were located 1.8 meters away from it. Their locations were labeled on the ground with numbers from 1 to 5. The participants occupied one of the Locations 1, 2 or 3; the other four had simulated social agents implemented as tripods holding a real-size photo of a female face.[3] The simulated faces were all the same to avoid potential confounds due to their appearance, and were positioned to be eye-level with the robot. The landmarks 0 and 6 were also on the ground for participants to indicate perceived gaze directions beyond the 1–5 range.

At the end of the study, participants were compensated with \$15 for one hour of their time. The protocol was approved by our local Institutional Review Board.

D. Procedure

When a study started, the participant first consented to participate in the activity and completed a demographics survey, including self-assessment questions [47] to verify normal or corrected-to-normal vision. Then, the experimenter introduced the robot to the participant and explained that their goal was to evaluate its gaze during the study.

The participant then sat in one of the Locations (1, 2 or 3) based on our study design, adjusting the height of their chair to be level with the robot's eyes. The person

[3]The picture was obtained from: `https://sydneyheadshot.net/wp-content/uploads/2018/03/02-resized.jpg`.

completed a short practice session to become familiar with the gaze evaluation procedure, and then 12 other sessions which provided data to evaluate our hypotheses.

Practice Session. The participant was given an iPad with a web survey to record observed gaze directions in reference to the 0 – 6 interval on the ground. When the session started, the robot was oriented forward, towards Location 3. Then, it repeatedly looked towards new gaze directions every 11 seconds. Every time gaze shifted, a ringtone was played and a letter marker was displayed on a monitor behind the robot so that participants would be aware that they needed to log a new gaze direction. In total, the robot gazed towards 8 gaze angles in the practice session: $-25°$, $11°$, $-1°$, $15°$, $-7°$, $3°$, $21°$, and $-9°$. It displayed each Gaze Behavior twice.

Gaze Evaluation Sessions. The rest of the study consisted of 12 gaze evaluation sessions. The sessions were organized in groups of 3 consecutive sets, with each set being completed at a different Location. Between each set, the participants were asked to take a break, stretch and relax. In the meantime, the experimenter swapped the location of the participants' chair with one of the simulated interactants according to the order of the conditions per our study design.

Each evaluation session followed a similar procedure to the practice, except for exposing the participant to 13 gaze directions and asking them to answer extra questions at the end. The 13 gaze directions corresponded to Angle Set A or B, depending which one the person experienced. The directions were conveyed by one Gaze Behavior for the full session. The final survey questions gathered opinions of gaze naturalness using the scale by Andrist and colleagues [48].

E. Measures

For each participant, we collected 156 observations of the perceived robot's gaze direction (13 gaze angles x 4 behaviors x 3 locations). We also logged the true gaze angle that the robot looked towards, the Robot Behavior exhibited in each case, and the participants' ratings for the four items in the gaze Naturalness scale from [48]. The items asked how *natural*, *humanlike*, *lifelike*, and *realistic* the gaze behavior of the robot looked like on a 7-point Likert responding format. The scale had high reliability in our study. Chronbach's alpha was 0.94, above the nominal 0.7 threshold.

F. Participants

We recruited 25 participants for the study by posting flyers in New Haven, CT, advertising the study in online volunteering lists, and word of mouth. However, we only considered the data from 24 participants valid, because the answers from the data from the very first participant of the study included several outliers, both in terms of gaze perception and naturalness ratings. We attribute these outliers to human error with our iPad interface, but they could also be due to misunderstanding of the procedure.

The participants were required to have at least 18 years of age, be fluent in English, and have normal or corrected-to-normal vision and hearing. Gender was balanced across Angle Set but the participants' age differed slightly (Table I). In total, the valid participants provided 3744 gaze evaluations (24 participants $\times$ 156 gaze directions) and 288 Naturalness ratings (24 participants $\times$ 4 conditions $\times$ 3 chairs).

TABLE I: Participant demographics."#M" indicates the number of males, and "#F" is number of females, "σ" is standard deviation, and "Fam. Rob." is familiarity with robots.

Angle Set	#M	#F	Avg. Age (σ)	Avg. Fam. Rob. (σ)
Set A	6	6	28.83 (13.78)	3.50 (1.17)
Set B	6	6	22.92 (6.11)	4.67 (1.87)
All	12	12	25.88 (10.86)	4.08 (1.64)

Three participants spent the majority of their childhood in China, Ghana, and Mexico, respectively; the rest grew up in the United States. Most participants were students. They reported using computers daily (M= 6.42, SE= 0.29) and being somewhat familiar with robots (M= 4.08, SE= 0.33) on 7-point Likert responding format (1 being lowest).

IV. RESULTS

We analyzed gaze perception error (for hypotheses H1 and H3), the perceived width of the cone of direct gaze of the robot (H1), and gaze naturalness (H2). Unless otherwise noted, we performed REstricted Maximum Likelihood (REML) analyses [49], [50] with Participant ID as random effect, and Gaze Behavior (E, H, EHM and EHA), Angle Set (A and B), and Location (L1, L2 and L3) as fixed effects. We included pairwise interactions in the models, checked for normality of the residuals, and used a significance level of 0.05. For significant results, we further conducted Tukey-HSD or T-tests post-hoc analyses as appropriate.

A. Perception of Gaze Direction

We inspected the responses from the participants by Gaze Behavior. As can be seen in Fig. 4(a), the E and EHM conditions seemed to lead to the most confusion; H seemed to lead to more accurate perception of gaze direction.

We conducted an REML analysis on the Error (difference) between the perceived angle and the true angle that the robot looked towards. To this end, we converted the discrete gaze directions provided by the participants relative to the floor landmarks to their equivalent angle relative to the robot: direction 0 corresponded to $-79.5°$, 1 to $-53°$, etc. The analysis resulted in significant differences per Location ($F[2, 3704]=238.14$, $p< 0.001$), Gaze Behavior ($F[3, 3704]=135.51$, $p< 0.001$), and their interaction ($F[6, 3704]=27.64$, $p< 0.001$). In terms of Location, L1 (M=$-12.29°$, SE=0.43) led to significantly more negative error than the rest. L2 (M=$-5.22°$, SE=0.38) also led to significantly more negative error than L3 (M=$-1.31°$, SE=0.37). The post-hoc on Gaze Behavior showed that the H and EHA conditions led to less negative error than the rest with M=$-1.64°$ (SE=0.39) and M=$-2.80°$ (SE=0.40), respectively. Also, the EHM condition (M=$-8.92°$, SE=0.47) led to significantly less negative error than E (M=$-11.75°$, SE=0.55). Lastly, the interaction between Location and Gaze Behavior suggested a bias towards negative angles (i.e.,

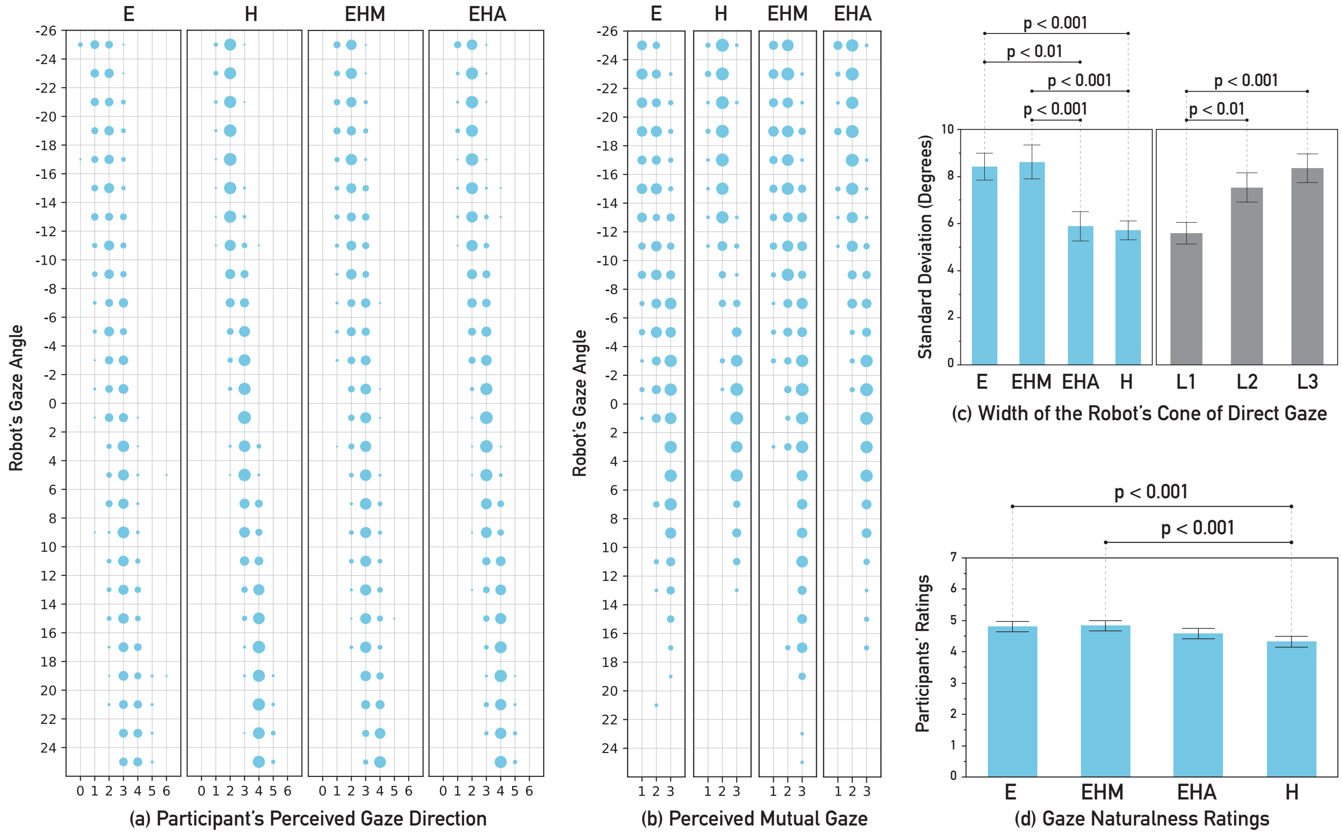

Fig. 4: Perception of the robot's gaze direction (a), of mutual gaze (b), width of the robot's cone of direct gaze (c), and naturalness ratings per Gaze Behavior (d). In (a), the horizontal axis indicates participant's perceived gaze direction (based on the floor landmarks from 0 through 6). In (b), the horizontal axis indicates the location in which participants perceived mutual gaze (e.g., when they were seated in Location 1 and thought that the robot gazed in that direction). The vertical axes correspond to the true angle that the robot gazed towards. The size of each circle is proportional to the number of occurrences in which people perceived a given gaze as pointing toward a given direction. Error bars are one standard error.

towards L1) especially with E and EHM. All the behaviors in L3 plus H and EHA in L2 led to significantly less negative Error than the rest. Lastly, the E behavior in L1 resulted in the most error, followed by EHM in L1, and then E in L2.

B. *(Approximate) Width of the Cone of Direct Gaze*

We inspected when participants thought that the robot was looking towards their Location (Fig. 4(b)). As in [11], we assumed that these were situations in which the robot established mutual gaze. We used this data to study variations in the perceived width of the robot's gaze cone [12].

We approximated the Width of the robot's gaze cone by calculating the standard deviation (σ) of the gaze angles in which participants felt looked at. Then, we conducted a Least Squares Regression analysis for the cone Width, including Gaze Behavior, Location and Angle Set as fixed effects as well as pair-wise interactions. Only Gaze Behavior and Location were significant, with p=0.0002 in both cases. As shown in Fig. 4(c), the Width of the robot's gaze cone was significantly higher with the E behavior (M=8.42, SE=0.57) and with the EHM behavior (M=8.62, SE=0.71) than with the other behaviors. In particular, the Width for the H behavior was M=5.71 (SE=0.40), while EHA led to M=5.88 (SE=0.62). In terms of Location, the Width in L1 (M=5.59, SE=0.46) was significantly smaller than in L2 (M=7.53, SE=0.62) and L3 (M=8.35, SE=0.61).

C. *Perceived Naturalness*

We conducted a REML analysis on the Naturalness scale. But the Shapiro-Wilk test rejected the assumption of normality of the residuals of the model (p=0.005). Further inspection of the data revealed two outliers, corresponding to one participant in the set of people who experienced the Angle Set B. This person provided bi-modal Naturalness ratings: he rated most Gaze Behaviors positively, but gave very low ratings of 1 and 2 (on 7-points) only to H in L2 and L3. We excluded the latter samples from the analysis, and re-computed the REML model. The significant results were the same as in the original analysis – as described further below. However, the residuals of the model did not violate the normality assumption anymore (p=0.227).

Gaze Behavior led to significant differences in Naturalness ($F[3, 246]=8.21$, $p< 0.001$). As shown in Fig. 4(d), the Head Only behavior (H) led to significantly lower Naturalness than the Eyes Only (E) and the Eyes & Head Misaligned (EHM) behaviors. Further, the REML analysis led to significant differences for Angle Set ($F[1, 22.01]=8.43$, $p< 0.01$) and the interaction between Angle Set and Location ($F[2,246]=6.50$, $p< 0.01$). In the former case, Naturalness ratings were significantly higher for the Angle Set B (M=5.29, SE=0.08) than for A (M=3.99, SE=0.13). In the latter case, the ratings for Angle Set B in L1 (M=5.51, SE=0.13) were significantly higher than for Set A in L1 (M=3.81, SE=0.21). Interestingly, the Naturalness ratings were negatively correlated with age ($r(284)=-0.37$, $p< 0.0001$), and positively correlated with participant's familiarity with robots ($r(284)=0.23$, $p< 0.0001$). However, age and familiarity with robots were not significantly correlated to each other ($p=0.90$).

V. DISCUSSION

During the study, we found evidence of the Mona Lisa effect with our semi-virtual robotic head, reinforcing prior work in this topic within robotics [11], [16]. In our pilots, some people moved in front of the robot and perceived its gaze direction as changing even though the eyes and the body of the robot were completely still. Because of the relevance of gaze in situated human-robot communication [20], [21], it is essential to consider these potential effects in HRI.

Perceived Robot Gaze. We found partial support for the hypothesis that the robot's head motion would reduce errors in the perception of gaze direction as well as the width of the robot's cone of direct gaze (H1). As expected, the E behavior led to significantly more error in comparison to the other behaviors. E also led to a significantly wider cone than H and EHA, but not EHM.

In comparison to [16], our results suggest that the effect of a robot's head orientation on gaze perception may be more pronounced with simple, cartoonish eyes than with human eyes rendered on a robot's face. The variations between our findings could also be due to the difference in the distance at which observers evaluated gaze between both studies.

Gaze Naturalness. The perception of how natural the gaze of the robot looked like varied based on Gaze Behavior, providing partial support for H2. The Eyes & Head Misaligned behavior was perceived as significantly more natural than the Head Only behavior, but Eyes & Head Aligned did not.

Our findings open up opportunities for varying a robot's cone of direct gaze dynamically during human-robot interactions. Because EHA led to less error in the perception of gaze direction and a narrower cone of gaze in comparison to EHM, it seemed like the best option among our Robot Behaviors for conveying gaze accurately and naturally with robots like ours. For a natural gaze but a wider cone of direct gaze, EHM or E seemed more appropriate.

Worth noting, Angle Set and the interaction between Angle Set and Location had a significant effect on gaze Naturalness. This result was not expected, because we balanced Angle Sets across participants. But further inspection of the data provided an interesting explanation: Naturalness ratings were significantly correlated with participant's age and familiarity with robots. Future studies should investigate this finding.

Effects of an Observers' Location. As expected, Location 1 led to significantly more error in the perception of gaze direction than Location 3 (H3). Interestingly, the width of the robot's cone of direct gaze was significantly smaller in L1 – more to the side of the robot – than in the other Locations. Taken together, our results suggest that both a robot's gaze behaviors and the observers' locations are worth considering when designing interactions for robots with screen faces.

Limitations & Future Directions. Our work is not without limitations. First, we controlled for many factors in our study to understand gaze perception at a fundamental level and prevent confounds. For example, we studied gaze perception with a single robotic platform, at a fixed distance and to one side of the robot. Additionally, our robot always displayed a 2D neutral, cartoonish face and our implementation of gaze shifts was simple in comparison to more anthropomorphic gaze controllers, e.g., [51], [17], [52]. Future work should study variations to these factors. Second, we found interesting results that suggested that age and familiarity with robots could affect perceptions of gaze naturalness, but we did not control for these factors in our study. Thus, more research is needed to corroborate this hypothesis. Third, our study was conducted with a single participant in a controlled environment that simulated a social interaction. We are excited about further investigating gaze perception with semi-virtual robotic heads in group settings with more than one user. In this respect, we suspect that the EHM and EHA behaviors can be used to subtly influence participation in group social interactions by helping regulate turn-taking.

VI. CONCLUSION

Our work contributed evidence that the interplay between head and 2D eye motion can alter how users perceive gaze rendered by semi-virtual robotic heads, both in terms of gaze direction and how wide users perceive the robot's cone of direct gaze. In particular, we found that the E and EHM behaviors resulted in wider perception of the robot's cone of direct gaze, evidenced also in more gaze perception error than H and EHA. This shows that coordinated gaze behaviors can enable robots to convey attention through gaze more narrowly or widely as needed. Additionally, our work provided evidence that the perception of gaze rendered by semi-virtual robotic heads can be affected by the relative location between the robot and the observer. Thus, observer location is an important factor to consider when designing gaze behaviors for social platforms. In future work, we plan to study gaze behaviors in group human-robot interactions and investigate whether they can subtly alter social dynamics.

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