Designing Robot Eyes and Head and Their Motions for Gaze Communication

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Abstract. Human eyes not only serve the function of enabling us "to see" something, but also perform the vital role of allowing us "to show" our gaze for non-verbal communication. The gaze of service robots should therefore also perform this function of "showing" in order to facilitate communication with humans. We have already examined which shape of robot eyes is most suitable for gaze reading while giving the friendliest impression, through carrying out experiments where we altered the shape and iris size of robot eyes. However, we need to consider more factors for effective gaze communication. Eyes are facial parts on the head and move with it. Thus, we examine how the robot should move its head when it turns to look at something. Then, we investigate which shape of robot head is suitable for gaze communication. In addition, we consider how the robot move its eyes and head while not attending to any particular object. We also consider the coordination of head and eye motions and the effect of blinking while turning its head. We propose appropriate head and eye design and their motions and confirm their effectiveness through experiments using human participants.

Keywords: Robot eye, gaze reading, facial design

1 Introduction

In the last decade, extensive research has been conducted into the use of robots in daily life that are able to engage in natural communication with people. In particular, service/communication robots are required to be able to perform not only verbal communication but also non-verbal communication. For human beings, one of the most important aspects of non-verbal communication is gaze, utilized, for example, to make eye contact and establish joint attention. We are developing a robot system that can attract a target person's attention, make eye contact, and then establish joint attention. We have revealed necessary robot actions depending on the positional relation

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between the human and the robot [7]. Our next target is to develop a robot system that can effectively perform such actions for gaze communication. Before developing an actual robot, we need to find the design principles of robot's shape and motion. It is needless to say that the most important part related to gaze communication is the eye. However, since the eye is a facial part on the head, we also need to consider the head.

Kobayashi and Kohshima [5] found that among primates only human eyes have no pigment in the sclera; moreover, human eyes also have the horizontally longest shape with the largest exposed area of sclera. Various explanations were offered as to why other primates have sclera colored in a similar fashion to their irises or the outside of their eyes. But all the explanations were based on the consensus that primates may avoid clearly showing their gaze. In contrast, human eyes have sclera with clearly different colors from those of the irises and the outside of the eyes. This enables the human gaze to be readily comprehended by others. Based on these studies, we determined a shape of robot eyes which conveyed a friendly appearance and a readily-readable gaze [8].

As the next step, we mainly consider the head in this paper. First, we investigate how the robot should move its head when it turns to look at something. We observe human head turning motions and find that the head speed is not constant during the action. We show that such human-like head turning make robot actions felt more natural through experiments using human participants.

Then, we examine the face/head shape. Face direction can be considered as a cue for gaze direction. Funatsu et al. [4] reported that gaze direction can be read by others through face direction with respect to body orientation when at a distance. In human-human communication, gaze direction tends to be recognized through head direction rather than eye direction [6]. Delaunay et al. [2] proposed a retro-projected robotic face and conducted experiments assessing a user's ability to read gaze direction for a selection of different robotic face designs. Through these experiments, they concluded that gaze-reading by the user was performed most successfully with a 3D-shaped mask with a human appearance. In this paper, we extend their study in a more systematic way. We prepare three faces: a flat face, a spherical face, and a spherical face with a nose. We show is the spherical face with a nose is most suitable for gaze reading through experiments using human participants.

Next, we consider idling motion, that is, how the robot should move when it does not attend to any particular person or object. Our hypothesis is that if the robot's idling action is seen natural, the robot may be more effectively able to attract people's attention when it really looks at them. Chikaraishi et al. showed that the gaze idling motion reacting to objects around especially those emerging or moving is more natural idling motion than that doing nothing and not reacting to any visual information [1]. We compare three gaze idling motions: reacting to high visual saliency positions (saliency motion), turning the head from side to side at a uniform velocity (horizontal uniform motion), and doing nothing (static motion). Experimental results are promising for the salient idling motion to effectively attract attention of people and induce joint attention although the number of participants was small and we need further investigation.

We also need to consider the coordination of the eye movements and head motions. In the field of research on driver assistance systems, there have been a number of studies about this. Doshi et al. reported [3] that human attention shifts can be divided into two types. When surprised, humans shift their gaze by means of the head following a motion of the eyes. In other words, the head pursues the motion of the eyes during an unintentional gaze shift. On the other hand, the opposite is true during an intentional gaze shift, such as when looking at a side mirror; the eyes follow the motion of the head. In this paper, we only consider the differences between the head turning actions with or without eye movements about the impressions on human observers. Here we include blinking in eye movements. When we investigated human head turning action, we found that many people blink when turning their head. Thus, we assume that blinking while turning the head may enforce the naturalness in robot motion. We have verified this assumption through experiments by using human participants.

Lastly we develop a robot head based on our proposed design principles. This paper presents our design principles and experimental results to support the principles.

2 Eye Shape Design

This section briefly describes our robot eyes and summarizes the results of our research on static gaze. For details see [8].

2.1 Development of Robot Eyes

We have developed a robot head with eyes enabling the functions of both "seeing" and "showing" gaze. For the latter function we employ projectors to display various types of eye images generated by computer graphics. We attached cameras to the robot head to enable the robot "to see." Furthermore, to enable precise control of the eye gaze towards a certain object, we establish calibrations among CG coordinates, camera coordinates and real world coordinates. An overview of our prototype robot head is shown in Fig. 1 (left). As shown in Fig. 1 (right), each of the eyes consists of a projector, a mirror and a screen. The eye images, generated by CG, are projected onto the hemisphere screen via rear-projection.

Kobayashi et.al [5] considered two parameters of eyes: the lid distance and the iridal diameter. Thus, we have designed this robot head in such a way that these pa-

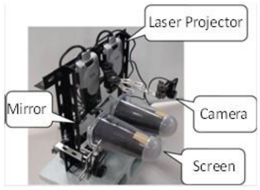


Fig. 1. (left) Overview of our proposed robot head;
(right) the inside of the robot head consisting of laser projectors, mirrors and screens.

rameters can be adjusted. The hemisphere mask can be changed to alter the lid distance (outline shape of the eyes), while the iridal diameter (iris size) can be easily changed because the irises are generated by CG. For the experiments described in the next subsection, we prepared three types of outline eye shape based on the width/height ratio: “round” (1:1), “ellipse” (1:0.5), and “squint” (1:0.25). In the same manner, we changed the iris size based on the ratio of the eye width and iris diameter: “large” (1:0.75), “medium” (1:0.5), and “small” (1:0.25). Consequently, we had 9 types (the combination of 3 outline shapes and 3 iris sizes) of eye design, as shown in Fig. 2. Among these, Fig. 2-E is the most similar to the human eye.

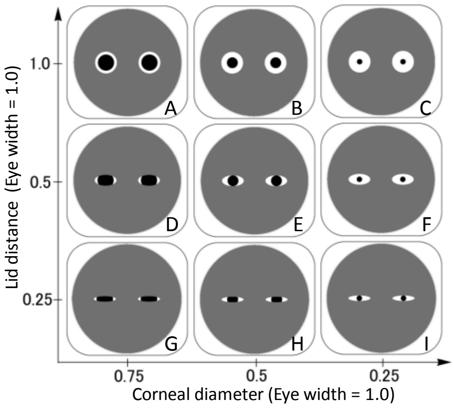


Fig. 2. Candidate designs for robot eyes derived by varying lid distance and iridal diameter.

2.2 Experimental Evaluation of Eye Shapes

We conducted two experiments. First, we performed an experiment to measure the perceived friendliness of robot eyes. We showed each of the nine pairs of robot eye design on an iPad to 105 participants (university students), and asked which seemed friendlier (Fig. 3). We analyzed the data by using Thurstone’s method of paired comparison. According to the results, there are two factors involved in determining perceived friendliness. One is the height of the eyes, and the other is the ratio of the iris area to the white area of the eyes. The results show that the friendliest robot face is one with eyes featuring a round outline shape and a large iris (as in Fig. 2-A).

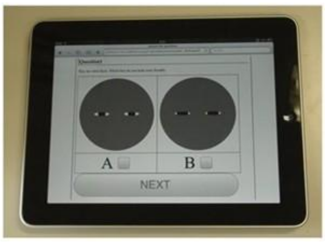


Fig. 3. Evaluating impression of robot eyes through the method of paired comparisons.

We next performed an experiment to analyze the relationship between the accuracy of gaze reading and the shape of the robot eyes by using the robot head proposed in the previous subsection. We evaluated errors in gaze reading using the 9 types of design candidates for robot eyes shown in Fig. 2. We lined up a series of markers between the participant and the robot head, as shown in Fig. 4. We asked each participant to state at which marker the robot looked. We divided the 36 participants into 3 groups. Each group experienced one type of outline shape with three different sizes of iris projected in a random order. We calculated the average errors for each design candidate.

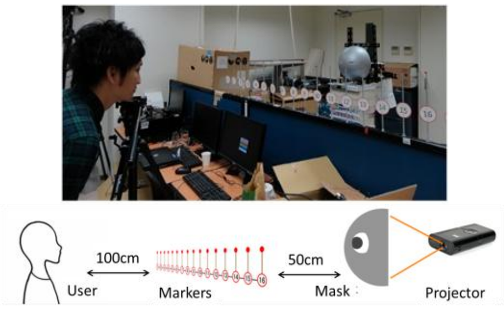


Fig. 4. Experimental scene from robot gaze reading.

Fig. 5 shows the result. In general, errors were fewer for eyes with a larger iris with respect to the sclera. A robot's gaze is therefore most readable by human users when performed by robot eyes with a round outline shape and a large iris (Fig. 2-A). In this experiment, the robot eyes did not move; they just appeared suddenly on the screens. Thus, we conducted a further experiment where the robot eyes would dynamically move toward the target marker. We compared the average errors between the static gaze and the dynamic gaze. The average errors for the dynamic gazes were smaller than those of the static gazes in all cases. From these experiments, we can conclude that among the 9 design candidates for robot eyes, the design with a round outline shape and a large iris (Fig. 2-A) is most suitable for gaze reading and conveying an impression of friendliness, and that a dynamic gaze is more effective than a static one.

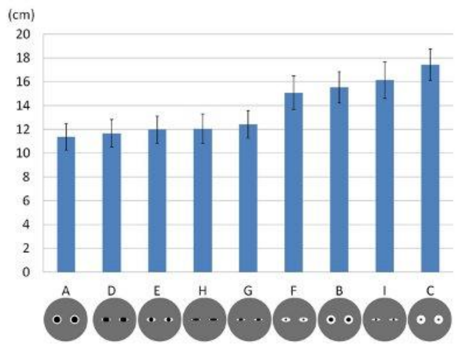


Fig. 5. Errors of gaze reading for each design candidate of robot eyes.

3 Head Turning Design

3.1 Observing Human Attentive Action

To learn how the robot head should be turned, with appropriate eyes, to express its visual focus of attention for establishing joint attention, we observed human eye and head motion during gaze shifting. Fig. 6 depicts a scene from the observation experiment. A participant is on the right in Fig. 6. We lined up a series of successively-numbered markers in front of each participant. The distance between the participants and the markers was 50 cm. We asked the participants to look at the marker we indicated. The camera in front of the participants filmed their behavior looking at the marker. Fig. 7 (left) shows an example of a captured image. An accelerometer (Wii remote controller by Nintendo Co., Ltd.) on the participant's head measured the speed with which they turned their head. When the accelerometer was rotated horizontally, it calculated an angular velocity at the time instance (Fig. 7, right). We used 39 participants, consisting of male and female university students around 20 years of age.

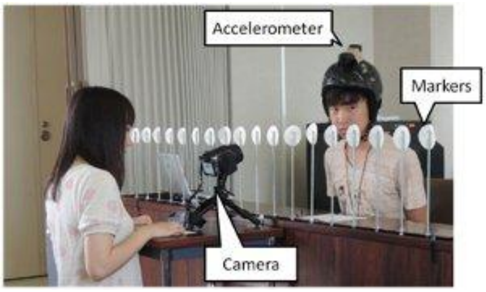


Fig. 6. Scene from experiment observing users turning their heads.

Fig. 7. (left) Image from the camera in front of a participant; (right) resulting graph of accelerometer's measurements (vertical axis: angular velocity, horizontal axis: time).

An example of a participant turning their head is shown in Fig. 8. The solid line shows the series of changes in the speed of head-turning in a large angle, while the dashed line shows the series of changes in the speed of head-turning in a small angle. As seen in Fig. 8, a large head turn and a small head turn take the same duration. Additionally, speed increases at first and then decreases, and a larger head turn involves a larger maximum speed. Most of the participants blinked their eyes when turning their heads. Almost all participants moved their heads before moving their eyes. Participants could likely predict the gaze destination because of the successive order of indicated markers.

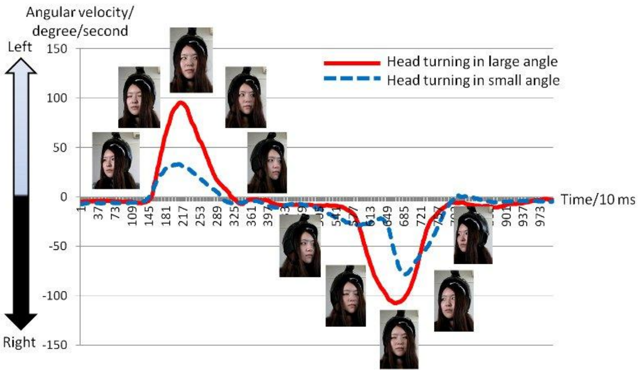


Fig. 8. Series of changes in speed of head-turning.

3.2 Evaluating Impressions of Robot Head-Turning

Based on the findings mentioned in the subsection 3.1, we prepared a robot so that the robot turned its head like a human, and conducted an experiment to evaluate the impression it made. Fig. 9 shows the measured results of the robot's head-turning.

We asked participants to observe the robot's head-turning behavior, both with an accelerated speed like humans and with a constant speed. After observing the two types of robot behavior, participants answered a questionnaire about their impressions. Fig. 10 shows a scene from the experiment. Participants observed each motion and answered questions about their impression of each.

In the questionnaire we asked the following six questions:

1. Which motion do you like? (Likeability)
2. Which motion do you think gives the impression of the robot turning its head to see something? (Robot turns its head to see something)

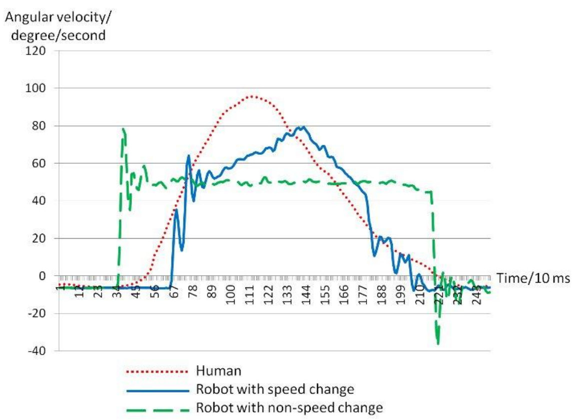


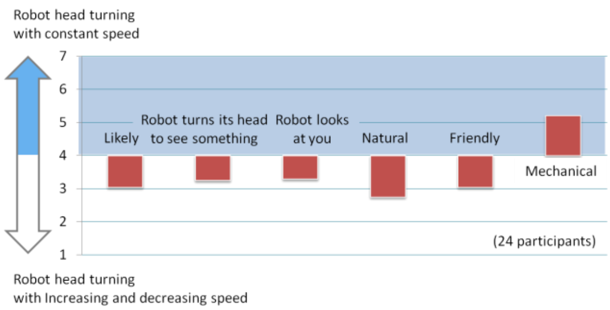
Fig. 9. Graph showing robot head-turning speed.

Fig. 10. Scene from experiment evaluating impressions of a robot's head-turning behavior.

3. Which motion do you think gives the impression that the robot looks at you? (Robot looks at you)
4. Which motion do you think is more natural? (Natural)
5. Which motion do you think appears friendlier? (Friendly)
6. Which eyes do you think are more mechanical? (Mechanical)

The participants evaluated each motion on a seven-point Likert scale. Which motion each participant saw first was random. We used 24 participants consisting of male and female university students around 20 years of age.

The results are shown in Fig. 11. Regarding the questions "Likeability," "Robot turns its head to see something," "Robot looks at you," "Natural," and "Friendly," the accelerated speed version was frequently chosen by the participants. We analyzed the results using a sign test. Significant differences were recognized for all items except "Robot turns its head to see something" ($p<.05$). Especially, there were large differences for "Natural." And the constant speed version was felt "Mechanical." The results indicate that the accelerated speed version is preferable for service robots.



	Likely	Robot turns its head to see something	Robot looks at you	Natural	Friendly	Mechanical
Average	3.042	3.25	3.29	2.75	3.042	5.21
p-value	.027	.17	.041	.0071	.035	.027

Fig. 11. Results of evaluation comparing impressions of head-turning motion.

4 Head Shape Design

Face/head direction is an important cue for gaze direction. Thus, we examined which shape of robot head is suitable for gaze communication. We prepared three robot faces for comparison experiments. Fig. 12 shows these faces: a flat face, a hemisphere face, and a hemisphere face with a nose. A tablet PC was used to show the flat face’s eyes. The rear-projection system described in Section 2 was used to display the eyes for the rest two faces.

(a) (b) (c)

Fig. 12. Developed robot faces. (a)Flat, (b) Hemisphere, and (c) Hemisphere with a nose.

The same manner and settings in subsection 2.2 were used in the experiment. Initially, the robot looks in front. Then the robot head rotates toward one of the markers at variable speed proposed in the previous section. The robot head returns back to look in the direction of the front marker at a uniform speed after 5 seconds. In this experiment, we move only the head. The eyes are fixed at the center.

A participant read robot gaze direction from each of three faces. We gathered 16 male and female participants around 20 years old.

The results are shown in Fig. 13. As shown in Fig. 13, the hemisphere face with a nose gives the smallest average error. We performed analysis of variance. Table 1 shows the results. There are significant differences in the results of Holm test (Table 2). These results indicate that the robot gaze direction is easier to be read in the order of the hemisphere face with a nose, the flat face, and the hemisphere face. Some participants even mentioned that they felt an arrow coming out from the nose of the hemisphere face with a nose.

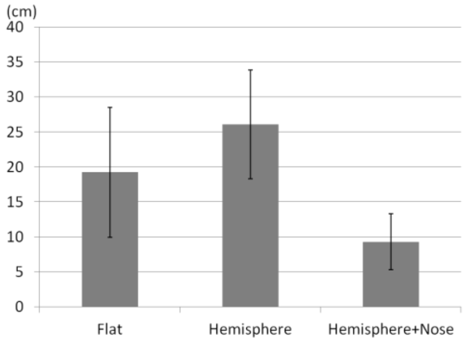


Fig. 13. Gaze reading errors for three faces.

Table 1. Analysis of variance for gaze reading accuracy.

A = {Flat, Hemisphere, Hemisphere with Nose}

S.V	*df*	*F*	η^2	*p*
A	2	19.67	.466	.727E-06
s x A	45			

Table 2. Multiple comparisons by holm.

Face	*Number of Data*	*Mean (cm)*
Flat	16	19.25
Hemisphere	16	26.06
Hemisphere + Nose	16	9.31
Comparison	*P*	
Flat < Hemisphere	.747E-02	
Flat > Hemisphere + Nose	.181E-03	
Hemisphere > Hemisphere + Nose	.243E-07	

5 Head and Eye Motion Design

5.1 Natural idling motion

We examined idling motion of the robot, that is, how the robot should move when it does not attend to any particular person or object. We hypothesized that if the robot's idling action is seen natural, the robot may be more effectively able to attract people's attention when it really looks at them. Thus we compared three gaze idling motions: reacting to high visual saliency positions (the saliency motion), turning the head from side to side at uniform velocity (the horizontal uniform motion), and doing nothing (the static motion).

Fig. 14 shows the experimental environment. Participants are asked to enter the room where the robot is placed and to observe the room and the robot so that they can answer questions about them later. They first stand 5 meters away from the robot and look around the room and the robot showing one of the three idling motions for 20seconds. Then they move to the side of the robot 1 meter away. The robot gazes at the target object indicated by the square in Fig. 14 when they approach. The experiment finishes 5 seconds later. We take the video for later analysis.

We prepare the following three idling motions. In the static motion, the robot continues gazing in front. In the horizontal uniform motion, the robot rotates its head from side to side at a constant velocity. In the saliency motion, the robot turns its head so that it may look at visually salient parts in the scene one by one. In Fig. 14 these parts that the robot looks at are indicated by the circles. In this motion, the robot shifts its face direction toward the participants when they are approaching the robot because moving objects show high visual saliency. Each participant experiences only one idling motion. The number of participants for each idling motion experiment is 10 (horizontal uniform motion) or 11(the others).

Fig. 14. Experimental environment.

After the experiment we asked the participants to fill in a questionnaire about impressions of the robot. However, we cannot find any significant differences in the results. We then analyzed the participants' actions from the recorded video. The purpose of our research is to develop a robot that can effectively establish joint attention with humans. Thus we examined whether or not the robot can establish joint attention when the robot turns its gaze toward the object indicated by the square in Fig. 14. In the salience motion case, 6 participants out of 11 (54.5%) turned to look at the object and the joint attention was established. In the horizontal uniform motion case, 4 participants out of 10 (40%) did so, whereas only 2 out of 11 (18.2%) in the static motion case. The results are promising for the salient idling motion to effectively attract attention of people and induce joint attention although the number of participants was small and we need further investigation.

5.2 Coordination of head and eye motions

We can move the eyes and the head to gaze at something. Thus we need to consider the coordination of these two motions. In this paper, we only consider the differences between the head turning actions with or without eye movements about the impressions on human observers. Here we include blinking in eye movements. When we investigated human head turning action described in section 3, we found that many people blink when turning their head. Thus, we assume that blinking while turning the head may enforce the naturalness in robot motion. We have verified this assumption through experiments by using human participants.

The setup of the experiment is shown in Fig. 15. A participant is seated in front of the robot. The robot explains to him/her the picture on the monitor. The robot looks in the direction of the monitor during explanation, but it turns its head toward the participant at some appropriate timings as we proposed in our guide robot study [9]. We prepare two motion patterns for this head turning. One is that the robot just turns its head by 60 degrees without any eye movements. The eyes are fixed in the center positions. In the other, the robot rotates both head and eyes each by 30 degrees simultaneously the robot also blinks during turning. Participants are just asked to listen to the robot's explanation. Each participant experience one of the two patterns. We use 51 participants, 24 for the head motion only and 27 for the head-eye combination motion.

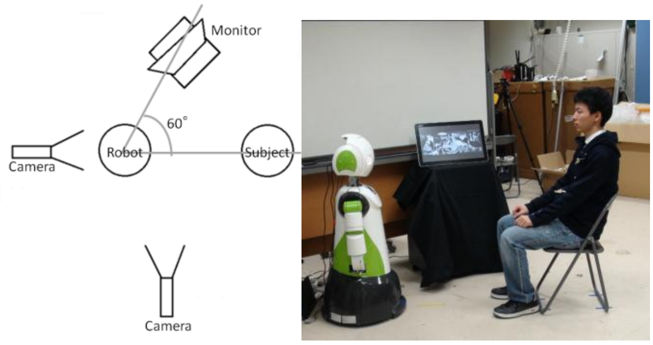


Fig. 15. The experiment setup.

After the experimental session, participants were asked to evaluate the naturalness of the robot in 7 steps by the Likert-scale (the larger, the more natural). The average scores are 5 for the head turning with eye motion, and 3.96 for the head turning without eye motion. There are significant differences by t-test (p=.001). Although we cannot separate the effects of total eye motion and blinking from this experiment, we can conclude that head turning with eye motion improves the natural impression.

6 Combining eye and head design

We have designed and made a robot head as shown in Fig. 16 based on our design principles. We have replaced the head of Robovie-R ver.3 by Vistone by this head. The inner structure of the head is the same as the one shown in Fig. 1. Although the original Robovie's face does not have a nose, the face center of the new robot head is protuberant like a nose. Furthermore, ear like parts are attached to both sides of the head to show the head direction more clearly.

Fig. 16. New robot head embedded in Robovie-R.

7 Conclusion and future work

Gaze communication is important for service robots interacting with humans. We would like to design robots suitable for gaze communication. The major parts related to gaze communication are eyes and head. We need to consider their static shapes and their motions. We have already examined which shape of robot eyes is most suitable for gaze reading while giving the friendliest impression. In this paper, we have considered the head shape design and the head motion. We also consider the combination of head and eye motions. We have found that the head motion at changing speed of slow-fast-slow like humans do can give natural and friendly impressions. We have also revealed that we can estimate gaze direction more correctly for a face with a nose than faces without a nose. We have further examined how the robot should move its head while not attending to any particular object. We have confirmed that moving both head and eyes can give more natural impressions.

In this paper, we just compared the head motions with and without eye movements. We would like to examine more complicated coordination of head motion and eye motion.

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