Meet Me where I'm Gazing: How Shared Attention Gaze Affects Human-Robot Handover Timing

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ABSTRACT
In this paper we provide empirical evidence that using humanlike gaze cues during human-robot handovers can improve the timing and perceived quality of the handover event. Handovers serve as the foundation of many human-robot tasks. Fluent, legible handover interactions require appropriate nonverbal cues to signal handover intent, location and timing. Inspired by observations of human-human handovers, we implemented gaze behaviors on a PR2 humanoid robot. The robot handed over water bottles to a total of 102 naïve subjects while varying its gaze behaviour: no gaze, gaze designed to elicit shared attention at the handover location, and the shared attention gaze complemented with a turn-taking cue. We compared subject perception of and reaction time to the robot-initiated handovers across the three gaze conditions. Results indicate that subjects reach for the offered object significantly earlier when a robot provides a shared attention gaze cue during a handover. We also observed a statistical trend of subjects preferring handovers with turn-taking gaze cues over the other conditions. Our work demonstrates that gaze can play a key role in improving user experience of human-robot handovers, and help make handovers fast and fluent.

Categories and Subject Descriptors
I.2.9 [**Robotics**]: *Operator interfaces, Commercial robots and applications;* H.1.2 [User/Machine Systems]: Human Factors

General Terms
Experimentation, Design, Human Factors, Verification.

Keywords
Human-Robot Communication, Handover, Head Gaze, Turn-taking, Nonverbal Communication

1. INTRODUCTION
In order for robots to take on more assistive roles for humans at homes and workplaces, it is essential for the robot to be able to successfully and fluently hand objects to people. Many application scenarios, be it in manufacturing or the home environment, can involve situations where it is useful for a robot to fetch and handover an object to a person. Implementing an effective human-robot handover, however, is a challenge. In human-human handovers, a great variety of subtle signals mediate the handover event. Body position, hand and arm pose, gaze, grip force, and the trajectory of these factors through time are used to communicate the intent to engage in a handover, when and where the handover is to occur, and help create a fluent and fast interaction while ensuring that the object is not dropped (e.g., [5, 11, 18, 26, 39, 40]). When a robot does not provide appropriate cues, human-robot handovers can fail in a variety of ways: people do not recognize that the robot is giving them an object [8], objects can be dropped [11], or people can feel uncomfortable or unsafe during the interaction [12, 23].

In this paper, we seek to improve human-robot handovers by investigating how gaze can be used to augment a handover event, subtly communicating handover location, handover timing, and providing acceptable social interaction signals.

Gaze cues, in either human-human interaction (HHI) or in human-robot interaction (HRI), have proven to be efficient for communicating attention [24, 31]. During a handover, givers use verbal or nonverbal cues to direct the receiver's attention to an object. Successful handovers typically take place when the two parties achieve shared attention on the same object. Previous studies [26, 39, 40] indicate that gaze can be used by robots to signal handover intent to users prior to the handover event. However, these studies did not explore the effect of robot gaze *during* the handover on the timing of the handover event.

We hypothesize that the use of gaze cues during human-robot handover can influence handover timing and the subjective experience of the handover by implicitly increasing communication transparency and perception of naturalness for the interaction.

In this work, we first conducted a human-human handover study to observe gaze patterns used during human-human handovers. To test the effect of gaze in human-robot handovers we implemented the two most frequently observed gaze patterns from the human-human study and a 'no gaze' condition on a PR2 humanoid platform and conducted an in-situ HRI experiment. We address the following two questions: 1. Can gaze improve the subjective experience of handovers, 2. Can gaze be used to produce faster, more fluent handovers. The key results from our study are as follows:

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- Subjects reach for the object significantly faster when the robot directs its gaze towards the intended handover location (shared attention gaze) than when no gaze cues are used.
- Subjects tend to perceive a handover as more natural, communicative of timing, and preferable when the robot provides turn-taking gaze in addition to shared attention gaze.

2. BACKGROUND

In this section, we outline a body of work on human-robot handovers and the use of gaze in HRI. In discussing human-robot handovers, we focus our discussion on studies where a robot is the giver and a human the receiver.

2.1 Human-Robot Handover

Previous research in human-robot handovers can be broadly categorized by the aspect of the handover under investigation: approach for handover, handover trajectory and pose, and the handover event itself.

Studies of approach for handovers consider situations where a mobile robot navigates towards a human to initiate a handover. These studies generally focus on human preference for approach directions and on creating robot behaviors that clearly communicate the intent to initiate a handover. Basili et al. studied how humans hold objects as they approach for a handover [5]. Koay and Sisbot studied human preferences for coordinated arm-base movement in handover approach [23]. Mainprice et al. designed an approach planner that considers the mobility of the receiver [28]. While our study does not involve a robot's handover approach (i.e., the participants approached our robot in our experiment), we used the above studies to guide our placement of the robot, as discussed in Section 4.1.

Other researchers have investigated handover trajectory and pose, reporting guidelines for how a robot arm should be positioned for handover and how that position should be achieved. In a series of studies, Cakmak et al. and Strabala et al. studied how handover trajectories and final handover poses can best signal the intent to initiate a handover [9, 40]. They found that the final handover pose should feature a nearly fully extended arm in a natural (human achievable) pose with the elbow, wrist, and distal point on the object positioned, respectively, from closest to furthest away from the body in all three dimensions. The object should be held in its canonical orientation (right side up) and positioned to allow easy grasping by the human. A related study emphasized the importance of the physical cues in human-robot handovers, showing that poorly designed handover poses and trajectories were often unsuccessful in communicating intent and ultimately resulted in handover failure [8]. They found that intent is best communicated by having high contrast between the pose used for holding the object and the pose used for handing over the object. We have followed the above guidelines in the design of our handover pose and trajectory, as described in Section 4.1.

Other studies have investigated the velocity profile of handover motions and have found that trajectories that minimize end-effector jerk make people feel safer in handover interactions [12, 17]. Other studies of handover trajectory include a human-based potential field planner for handover trajectories [21].

Chan et al. studied the actual handover event, measuring grip and load forces in human-human handovers and using these data to design a robust robot handover grip controller that imitates human handover behaviour [11]. We have adapted this controller for use in our study.

2.2 Gaze in Human-Robot Interaction

Gaze is an important and useful cue in HHI. People repeatedly look each other in the eye during social interaction and people do not feel that they are fully engaged in communication without eye contact [2]. Studies in psychology have shown various functions of gaze in social interaction, such as seeking and providing information, regulating interaction, expressing intimacy, exercising social control, etc. [2, 24, 33]. Gaze can be named differently in different social situations [31]; for example, mutual gaze or eye contact is defined as two people looking into each other's face or eye region [41], while deictic gaze or shared visual attention is defined as one person following the other's direction of attention to look at a fixed point in space [7].

Previous work has shown the importance of gaze in HRI. For example, Staudte and Crocker [38] demonstrated that humans react to robot gaze in a manner typical of HHI. Since gaze behavior is closely linked with speech [4], much work has been done on the conversational functions of gaze in HRI [25, 27, 29, 30, 32, 42]. Gaze is particularly effective in regulating turn-taking during human-robot conversation. Kuno et al. [25] developed gaze cues for a museum guide robot to coordinate conversational turn-taking. Matsusaka et al. [29] used gaze cues to mediate turn-taking between participants in a group conversation.

Another large body of literature focus on using gaze to direct people's attention in HRI [6, 15, 20, 34, 36]. Gaze was combined with pointing gestures in [6, 15, 20] to direct people's attention, which the authors believed would make the interaction more human-like [6] while minimizing misunderstanding [15]. In [34] four types of "connection events" were identified from HHI videos, namely directed gaze, mutual facial gaze, adjacency pairs and backchannels. Implementing them in an HRI game showed a high success rate in forming human-robot connection or joint attention. In [36], people directed their attention to the robot more often in interactions where gaze was present, and people found interactions more appropriate when gaze was present.

Introducing gaze cues can also benefit HRI in other ways. In [30] and [37], gaze increased human performance in certain human-robot tasks. In [25] and [36], gaze heightened human-robot engagement and in [27], gaze cues contributed to the perceived naturalness of a communicating robot.

In the study of human-robot handovers, other researchers have shown that gaze can be useful in communicating the intent to initiate a handover. Lee et al. [26] studied human motion and gaze cues as people approached each other for handovers. They found that people looked at the object or at the receiver as they approached the receiver. Strabala et al. [39] examined the signals that humans use to communicate handover intent before a handover takes place. They initially acknowledged gaze as one of the important features that mark the difference between different phases in handover, but they did not find gaze to be an effective predictor of handover intent. In contrast, Kirchner et al. [22] demonstrated how robot gaze can be effective in targeting an individual recipient out of a group of people for a robot initiated handover. Atienza and Zelinksy [1] augmented handover interactions with gaze, demonstrating a system that allowed a human to request an object for handover by looking at it.

While the above studies addressed gaze in pre-handover cuing and communication of intent to handover, in this study we examine the use of gaze *during* the handover event. Although the effectiveness of gaze in regulating handover intent remains an open question, gaze may have a positive effect when used during the handover event, since it helps establish shared attention and has been shown to improve human-robot tasks. Hence, we hypothesize that gaze may be useful in improving the handover itself by establishing shared attention and signaling the robot's end of turn.

3. HUMAN-HUMAN HANDOVER STUDY

To assist our human-robot handover experiment design, we carried out a study on human-human handover of a bottle of water, as shown in Figure 1, to observe the gaze behaviour of the giver during the handover. While other researchers have observed gaze in human-human handovers (e.g., [39]), these studies focused on gaze cues *before* handover. For our current study, we augmented these previous results with a study focusing on gaze *during* the handover event.

Twelve volunteers (10 male, 2 female) participated in this study. The giver was asked to handover ten bottles from a side table to the receiver one at a time. The receiver was asked to bring the bottles to a collection box about two meters behind them one at a time, requiring him/her to walk away from the giver between each handover. This process repeated until all ten handovers were completed. Each participant performed the role of the giver, then was paired with another participant and performed the role of the receiver, resulting in a total of twelve giver-receiver pairs.

The giver and receiver were instructed not to talk during this process. The giver was also instructed to pick up the bottles from the side table only after the receiver returned from the collection box and had put his/her hands on the table. By requiring the receiver to turn and walk away, the common attention between the giver and the receiver was interrupted after each handover and participants needed to re-connect for the next handover.

Through a frame-by-frame analysis, we annotated the givers' gaze patterns from video recordings of the 120 handovers, and found the following two dominant gaze patterns.

Shared Attention Gaze (Figure 1a): The most frequent gaze pattern (68% of all handovers observed) consists of the giver gazing at a projected handover location as s/he reaches out to execute the handover. After picking up the bottle, the giver turns to face the receiver, looks down at a midpoint between the giver and the receiver, and keeps the gaze there until the receiver takes control of the bottle. This midpoint is approximately where the handover takes place. There is no eye contact between the giver and the receiver throughout this handover gaze pattern.

Turn-Taking Gaze (Figure 1b): In 13% of handovers, we observed a slight variation from the Shared Attention Gaze. In addition to gazing at a projected handover location while reaching out, the giver *also* looked up to make eye contact with the receiver near the end of the handover motion, at approximately the time that the receiver made contact with the bottle.

Other handover gaze patterns consisted of the giver looking at the receiver's face throughout the handover (8%), the giver looking at the receiver's face and quickly glancing at the bottle when the receiver is about to touch the bottle (8%), or the giver glancing at the receiver before but not during handover (4%).

4. METHODS

To examine the impact of robot gaze on human receiver behavior, we used a PR2 humanoid mobile robotic platform (Willow Garage Inc., Menlo Park, CA) with a pan-tilt head and two 7-DOF arms, each with a two-fingered, 1-DOF gripper. In the following, we (Section 4.1) outline the physical handover cues used by the PR2; (Section 4.2) describe the three experimental gaze conditions inspired from the human-human handover study; and (Sections 4.3-4.4) outline our experiment design and technical implementation.

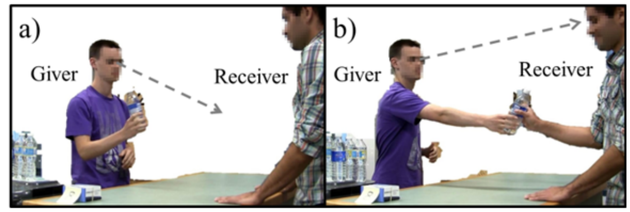

Figure 1. Demonstration of two frequently observed gaze patterns from the human-human handover study. a) shared attention gaze: the giver looks at the location where the handover will occur, and b) turn-taking gaze: the giver looks up at the receiver after the shared attention gaze.

4.1 Physical Handover Cues

In our experiment, based on [5] and [23], the robot was positioned such that it was facing the participant approximately 1 meter away.

The robot executed the handover with its right gripper, as recommended in [23]. In the beginning of each handover, the robot starts its motion at the *grasp position* with its end-effector prepared to grasp a bottle sitting on a table at the robot's right side. When subject is ready, the end-effector grabs the bottle (marking a *start time*, $t=0$ of the interaction), then moves the bottle horizontally to a position in front of the robot's centreline (*ready position*). Then the robot moves from the *ready position* forward to the *handover location*. We predefined joint-angle goals of the *grasp position*, *ready position*, and *handover location* such that when the robot's end-effector is extended, the arm is positioned in a natural pose: the elbow located below the shoulder, and the gripper located below the distal point on the bottle, as shown in Figure 3. We designed our *handover location* in accord with the recommendations of previous work [22, 26]. The three locations are constant for all three gaze conditions. While other researchers have proposed handover controllers that adapt to the position of the human's hand, for example [14], we chose to maintain a constant *handover location* and only vary gaze cues used during handovers.

When the robot's arm reaches the *handover location*, the robot waits for a participant to grasp and pull up on the object. The force the gripper exerts on the bottle is a linear function of the downward force exerted by the bottle as described by Chan et al. [11]. Thus, as the subject takes the weight of the bottle, the robot releases its grip (marked as the *release time*). The PR2's fingertip pressure sensor arrays were used to realize Chan et al.'s handover controller.

Finally, after releasing the object, the robot returns to the *grasp position*, ready to grasp and lift the next object.

4.2 Experimental Gaze Cues

In this study, the PR2 robot expressed gaze through head orientation. Imai et al. [19] showed that robot head orientation can be an effective substitute for human-like gaze and that head orientation is interpreted as gaze direction. In order to minimize any possible confusion regarding the robot's gaze direction, we used a single object for the handovers.

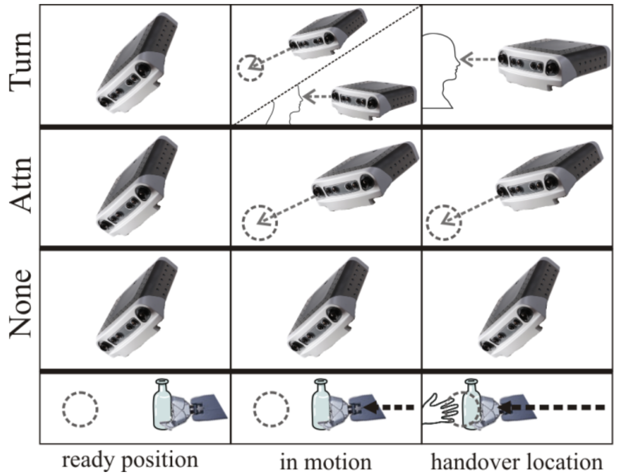

Figure 2. Depiction of gaze cues: No Gaze (None), Shared Attention Gaze (Attn), and Turn-Taking Gaze (Turn). In the Turn condition, the robot shifts its gaze from the handover location to the human's face midway through the handover motion.

We tested three different gaze patterns in human-robot handovers, as shown in Figure 2. In all conditions, the robot's gaze tracks its end-effector from the *grasp position* to the *ready position* as though the robot is attending to the acquisition of the bottle. When the end-effector arrives at the *ready position*, the robot's head is tilted downwards towards the end-effector. Only when the robot arm transitions between the *ready position* to *handover location* does the robot transfer its gaze according to the following gaze patterns.

The **No Gaze (None)** condition is our baseline. The robot head remains looking down towards the ground while the end-effector extends forward for the handover.

The **Shared Attention (Attn)** gaze condition models the most frequently observed gaze pattern from our human-human handover study. When the robot starts to move from the *ready position* to the *handover location*, it smoothly transitions its gaze (head orientation) from the bottle to the location in space where the handover will occur, as an implicit cue intended to direct the human's attention towards the projected *handover location*. With this condition, we test the hypothesis that shared attention can be established through gaze during handovers, and that doing so benefits the handover interaction. Establishing shared gaze at an object or location can serve to direct shared attention (e.g., [20]) and can aid in the successful execution of human-robot cooperative tasks (e.g., [37]).

The **Turn-Taking (Turn)** gaze condition is also derived from our human-human handover study, and is analogous to the second most frequently observed gaze pattern. When the handover trajectory begins, the robot smoothly transfers its gaze to the *handover location*, as in the Shared Attention condition, but then shifts its gaze up to the human's face in a quick motion, reaching the final gaze position at approximately the same time that the handover motion completes. Here we test two hypotheses: that (a) this gaze shift can cue handover timing, and (b) looking at the face can improve the subjective experience of the handover. This type of gaze shift has been shown to be a meaningful human-robot turn-taking cue [10] and mutual gaze can increase the sense of engagement and naturalness in human-robot interactions [27, 36].

4.3 Experimental Procedure

We conducted a paired-comparison handover study in a controlled room. The study took place on the day of a university orientation event such that many and diverse naïve participants could be rapidly recruited during the public event. We used a balanced incomplete block design (v=3, b=96, r=64, k=2, λ=32) to both support rapid trials (maximum 5 min.) and include only naïve reactions: each participant evaluated one of the three condition pairings. Condition order was randomized and presentation order counterbalanced among trials.

Participants provided informed consent, then entered the room where verbal instructions were given (Figure 3). They were told to stand at a marked area facing the robot, and informed they would participate in a handover interaction. Participants were also told that the robot would pick up the water bottle placed beside it and hand it to them. They were asked to take the bottle from the robot whenever they felt it was the right time to do so. To avoid unintended cuing, during handovers the experimenters sat out of the field of view of participants.

After receiving the first bottle, participants placed the bottle in a box approximately 3 meters behind him/her. This served as a washout between handovers, breaking the participant's focus on the robot and the handover, as was done previously in [8]. Participants then returned to the same marked area in front of the robot and participated in a second handover. Participants were permitted to keep the last bottle given to them by the robot.

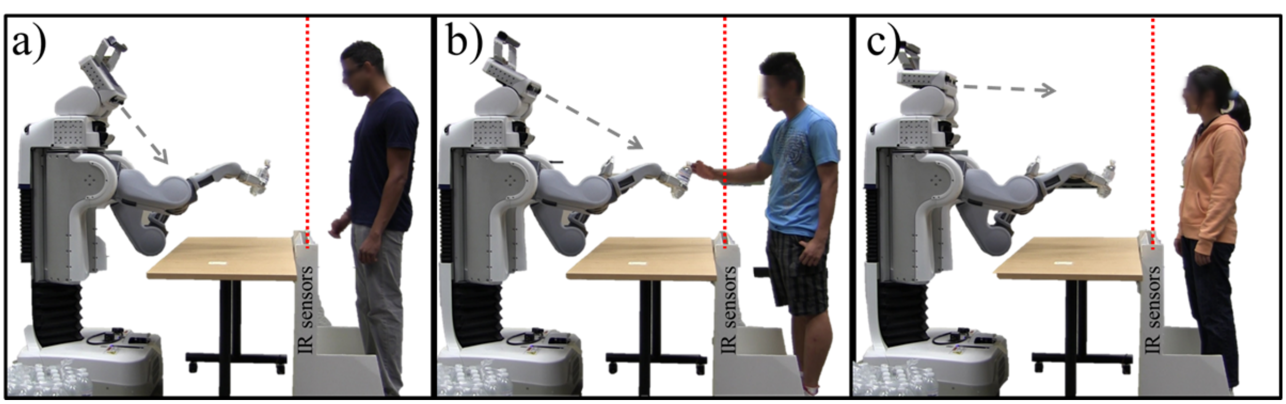

Figure 3. Demonstration of the experimental set-up and the three conditions at the *handover location*: a) No Gaze; b) Shared Attention; and c) Turn-Taking. An array of infrared sensors was located at the edge of the table. The red dotted lines represent the location where subject's reach motion is detected. Subjects stood at a specified location marked on the floor.

During each handover, we timestamped the following events: start of robot motion (*start time*), end of robot motion (*end of motion time*), start of release of the robot's gripper (*release time*), and the participant's first reach for the object (*reach time*) as measured by the motion sensor array described in Section 4.4.

After the second handover, participants left the room and completed a short questionnaire comparing the two handovers on three subjective metrics: *overall preference*, *naturalness*, and *timing communication*. For each of the following three questions, participants were asked to select either the first or second handover:

1. Which handover did you like better, overall?
2. Which handover seemed more natural?
3. We think that timing is important in human-robot handovers. Which handover made it easier to tell **when**, exactly, the robot wanted you to take the object?

Participants could also provide additional comments.

4.4 Technical Implementation

To control the PR2, we extended the Robot Operating System (ROS) [35] with a series of software modules coordinated via the Blackboard architectural design pattern [16] (Figure 4).

One module controlled the robot's arm and another, its head. The head-control module provided object tracking functionality for bringing the object to the *ready position*, and a smooth, fast gaze transition (average 90 degrees/second) functionality to enable the Shared Attention gaze and Turn-Taking gaze conditions during the handover motion.

An independent module logged quantitative measurements of robot's *start time*, *end of motion time*, and *release time*.

Reach Time Detection: An array of three passive infrared motion sensors (SEN-08630, SparkFun Electronics, Boulder, CO) configured as a light curtain was placed at the edge of the table (Figure 3), and was used to detect the start of the participant's reach (*reach time*) triggered by the participant's hand crossing the table edge. An Arduino microprocessor relayed the sensor reading to the PC controlling the robot. Sensor readings were logged and time-synchronized with the robot.

5. RESULTS

A total of 102 volunteers participated in our experiment. We rejected six records (instruction not followed), and analyzed data from 96 participants (63 male, 33 female; age $M=23$, $SD=5.59$). Due to technical error, *reach time* was not logged in the second handover for five of the participants. This did not affect our analysis of handover timing, since we are interested in only the first handover *reach time*. No other technical failures occurred and all handovers were successful (no bottles were dropped).

5.1 Handover Timing

Figure 5 shows the distribution of three key times: the robot's *end of motion time*, participant's *reach time*, and robot's gripper *release time*. All times are measured relative to *start time*.

We conducted a one-way ANOVA on participants' *reach time* across the three conditions. Since we found a significant learning effect between the first and second handover trials ($t(90)=4.21, p<.001, d=0.43$) where *reach time* is earlier in the second handovers, and our goal was to understand naïve behavior, we only used the *reach time* collected during the first of the two handovers performed by each participant. The entire robot motion

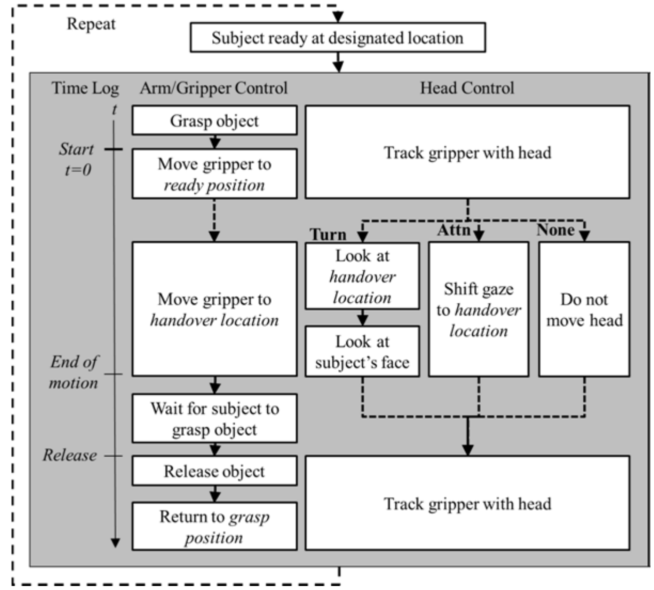

Figure 4. Experiment system flow diagram

from the *grasp position* to the *handover location* consistently took 2.02 seconds ($SD=0.01$).

Participants' *reach time* varied across the three gaze conditions ($F(2, 93)=6.49, p<.005$) as plotted in Figure 5; post-hoc analyses used a Bonferroni correction. Participants reached for the object significantly earlier with Shared Attention ($M=1.91, SD=0.52$) than with No Gaze ($M=2.54, SD= 0.76$) ($p<.005$). Note that the mean *reach time* for Shared Attention occurs before the robot has stopped moving at the handover location (*reach time* < *end of motion time*). No significant differences were found between Shared Attention and Turn-Taking ($M=2.26, SD=0.79$), or between Turn-Taking and No Gaze.

5.2 Subjective Experience

To contrast *overall preference*, perceived *naturalness*, and *timing communication* across the three gaze patterns during handovers, we employed Durbin's test [13] – analogous to a Friedman test for rank data, but adapted to balanced incomplete block designs – on our questionnaire data.

We checked for possible gender effects using Mann-Whitney U tests. No significant effects of gender were found (*overall preference*: $U = 935.0, p=0.23, r = 0.12$; *naturalness*: $U=918.5, p=0.18, r=0.14$; *timing communication*: $U=935.5, p=0.22, r=0.12$). We conducted one-sample Wilcoxon signed rank tests to observe potential bias in selecting the first or second handover experience in the questionnaire. We found a significant bias towards selecting the second handover on the *timing communication* metric ($Z=2.22, p<.05$) and a weak trend to select the second handover on both *overall preference* and *naturalness* metrics ($Z=1.62, p=0.11$ and $Z=1.41, p=0.16$, respectively). The rank data collected using the questionnaire is insufficient to correct for this bias statistically.

Given this general bias to select the second handover, we believe that finding statistical significance to $\alpha=0.10$ in questionnaire results is noteworthy. Hence, we also report our observation of trends (results having $p<0.10$; Table 1).

Overall Preference: We did not find a significant difference in user preference across the three gaze conditions ($T2=2.04, p=0.14$). However, one-tailed pairwise comparisons demonstrate

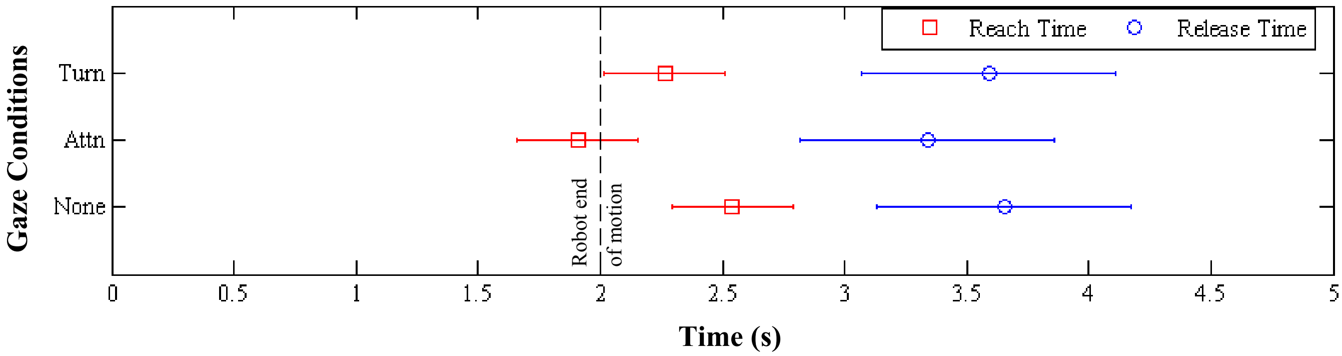

Figure 5. Handover timing. All times are measured with respect to the robot's start of motion at t=0. The dashed line at 2 seconds indicates the end of robot motion at the handover location. Reach time indicates the participant's reach toward the proffered object crossing the infrared sensors. Note that in the case of the Shared Attention (Attn) condition, participants start to reach before the robot has reached handover location. The mean reach time for the Shared Attention condition is significantly earlier than that of the No Gaze (None) condition. The error bars indicate the 95% confidence intervals.

a trend for preference toward Turn-Taking over No Gaze ($p<0.10$) and Shared Attention ($p<0.10$) conditions.

Naturalness: We did not find any significant difference in perceived naturalness of the handovers across the three gaze conditions ($T2=1.82$, $p=0.17$). However, participants tended to choose Turn-Taking as more natural than Shared Attention ($p<0.10$) but not over the No Gaze condition.

Timing Communication: No significant differences were found in the perceived communication of timing across the gaze conditions ($T2=1.65$, $p=0.20$). However, participants tended to choose Turn-Taking over Shared Attention ($p<0.10$), but not over No Gaze, as easiest to communicate handover timing.

In total, 59% of all participants provided additional comments (optional) on the questionnaire. Twelve subjects who experienced the Turn-Taking condition explicitly used words such as "head motion", "eye contact" or "looking at me" and expressed the condition in a positive light (e.g., P90 compared No Gaze with Turn-Taking: "During second handover [Turn-Taking], robot made eye contact, which made it easier to tell when the bottle should be taken."; P10 compared Shared Attention and Turn-Taking: "I liked it when robot looked at me. That confirms it's good to take."). However, another twelve subjects expressed that they did not notice any difference between the conditions.

Table 1. Ranking of questionnaire results. Each cell represents the number of people who chose the row condition over the column condition. * indicate pairwise comparisons that are significant to p<0.10 (none were significant to p<0.05). Note that we observed participants' bias to select the second handover experience regardless of experiment condition.

Overall Preference

	Turn	Attn	None
Turn-Taking	0	**21***	**19***
Shared Attention	11	0	17
No Gaze	13	15	0

Naturalness

	Turn	Attn	None
Turn-Taking	0	**20***	19
Shard Attention	12	0	19
No Gaze	13	13	0

Timing Communication

	Turn	Attn	None
Turn-Taking	0	**21***	18
Shared Attention	11	0	19
No Gaze	14	13	0

6. DISCUSSION

Building on previous work that studied communication of intent to handover using gaze, our study explored the impact of robot gaze on human-robot handover timing and user perception of the handover experience. Our results show that participants reached for the proffered object significantly earlier when the robot performed a shared attention gaze at the projected handover location. In fact, participants reached for the object even before the robot had arrived and stopped at the *handover location* (a mean of 0.11 seconds before the *end of motion time*). This is in contrast to the No Gaze condition where the mean reach time is 0.52 seconds after the robot's *end of motion*.

In our experiment, participants were explicitly told that the robot would be handing over objects to them and that they were to take the object from the robot. In addition to this foreknowledge, our robot used highly contrasting poses between the *ready position* and the *handover location* which, according to [8], makes the robot's intent to handover very clear. Hence, it is unlikely that the observed difference in timing between the gaze conditions is due to uncertainties in understanding the robot's handover intent. Rather, our results suggest that the robot's gaze at the projected *handover location* supplements the communicated intent with implicit information on *where* the handover should take place. This may be helping to establish shared attention on the handover location even before the robot arrives there, naturally allowing participants to respond and meet the robot at the location earlier than when such a cue is absent. Thus, our result best support an increase of fluidity in execution of the handover as it takes place.

However, the role of mutual gaze used in the Turn-Taking condition requires further investigation. In the beginning of the robot's handover motion, the robot expresses the same locational, shared attention gaze in both the Shared Attention and Turn-Taking conditions. Hence, we were surprised to find that the *reach time* of the Turn-Taking condition is not significantly earlier than that of the No Gaze condition.

With the Turn-Taking condition we intended to test two hypotheses: that the Turn-Taking gaze would cue handover timing, and that looking at the participant's face would improve the subjective experience of handover. While we observe a trend suggesting that the robot's gaze directed at the face improves the subjective experience of handover, it appears that the shared attention gaze cues the handover timing instead of the mutual, turn-taking gaze. It may be that the mutual gaze we implemented served the function of acknowledgement rather than our intended function of turn-taking. We suspect that qualitative differences in participants' reaction may exist between the Shared Attention and Turn-Taking conditions. For example, participants may have started to respond to the robot's shared attention gaze in both conditions but, prior to being detected by our reach sensor, saw the robot's turn-taking gaze and stopped to make eye contact before continuing to reach across the table.

This raises unexplored questions about how participant's *reach time* is affected by the timing of the robot's gaze. How much would varying the robot's gaze timing affect human *reach time*? Is the timing of the robot's gaze a more dominant cue than the location the robot is gazing at? That is, would a robot that shifts its gaze from the object directly to the person's face during handovers have the same effect as the Shared Attention condition? Would we see changes in participants' reach direction if the robot gazed at a different location? Without a thorough qualitative analysis, it is difficult to tell, with accuracy, if and when shared attention is established with the participant. A separate experiment with a gaze tracking device would help answer these questions, but this is beyond the scope of this study.

It is important to note that our results may be representative of naïve participants only, where novelty effects may have motivated them to observe the robot more carefully than they would if they were more familiar with the robot. Unsurprisingly, we observed a significant training effect in our *reach time* data, as well as a bias toward describing the second handover experience more favourably in our questionnaire regardless of the condition experienced. Some of the participants' comments suggest that in certain cases, people did not pay attention to the head of the robot at all. Indeed, we suspect that in many human-human handover scenarios, especially those that are repetitive or trained, people do not use gaze cues at all yet succeed in object handover. Thus robot gaze cues may not have the same effect on trained or familiarized users.

Although the earlier *reach time* of participants in a handover may seem more similar to natural, unscripted human-human handovers, this may not necessarily be desired in some human-robot handover situations. Depending on the handover controller implemented on a robot, handover timing may need to be controlled such that people naturally grab the object only when it is safe to do so. Many of the handover controllers that modulate the release time of the object are built for cases where the robot's gripper is already at the handover location before people grab the object. A situation where the object is grabbed before the robot is ready to release the object could lead people to pull hard on the object, possibly damaging or dropping the object, or resulting in a negative perception of the robot.

7. CONCLUSION and FUTURE WORK

In this paper, we demonstrated how a robot's humanlike use of gaze expressions in human-robot handover can affect the timing of the handover event. Once the intention to handover is established, providing a gaze cue to the projected handover location seems to offer rich gestural information about the handover event, and allows users to reach for the proffered object sooner, even before the robot arrives at the location. Our results also suggest that users may tend to prefer eye-contact gaze in addition to the locational, shared attention gaze. Part of our future work will further explore this trend.

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