Imagine you have made the peanut butter sandwich and passed it to Mary to cut it in half. Which of the following two actions is **more relevant**?

A. Mary starts crying since she cut her finger with a knife.

B. You begin to boil the water to boil the eggs for your second sandwich.

C. Equally relevant.

Figure 5.5: Example relevance question.

choose that the strong emotional circumstance will be more relevant; however, human participants generally selected adherence to the collaboration plan to be more relevant.

5.2.4 Discussion

As shown in the preceding results tables, the human participants agreed 100% on some questions, while on some other questions there was a much lower level of agreement. Our results indicate that people largely performed as our hypothesis predicted. The very small p-values indicate that the data set is not random; in fact, the high percentage of similarity confirms our hypothesis and shows that the algorithms can help us to model appraisal in a collaboration. The very low level of agreement on a handful of questions may indicate algorithm components that require further refinement before implementation; therefore, we made limited changes to our algorithms in light of this study.

5.3 End-to-End System Evaluation

As mentioned earlier, collaborative robots need to take into account humans' internal states while making decisions during collaboration. Humans express emotions to reveal their internal states in social contexts including collaboration [35]. Due to the existence of such expressions, robots' emotional-awareness can improve the quality of collaboration in terms of humans' perception of performance and pref-

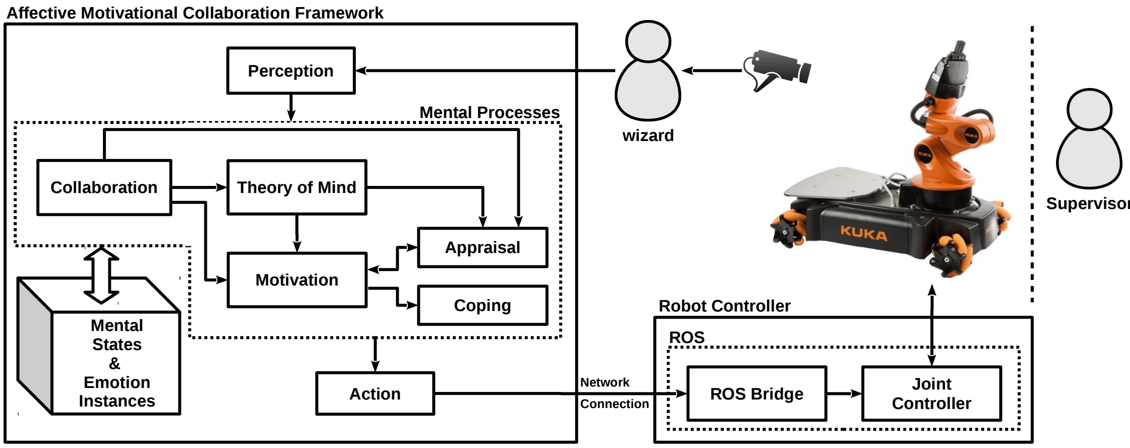

Figure 5.6: Experimental setup for end-to-end system evaluation.

erences. Hence, collaborative robots need to include affect-driven mechanisms in their decision-making processes to be able to interpret and generate appropriate responses and behaviors. Our aim in this experiment was to study the importance of emotional awareness and the underlying affect-driven processes in human-robot collaboration. We examined how emotional-awareness impacts different aspects of humans' preferences by comparing the results from our participants collaborating with an affect-aware versus an affect-ignorant robot.

5.3.1 Experimental Setup

The setup of this user study included three separate parts. The first part incorporated the Affective Motivational Collaboration framework consisting of all Mental Processes (see left-side of Figure 5.6) as we described in Chapters 3 and 4. The second part was implemented to receive action commands from the framework and forward them to the robot to control joints and actuators (see right-side of Figure 5.6). A wizard was the third part of this setting. The wizard did nothing but inform the robot/framework whether the current task performed by either the robot or the participant was achieved successfully. The wizard was completely invisible to the participants, and the wizard had no impact on the robot's decision other than providing input regarding tasks' failure or success.

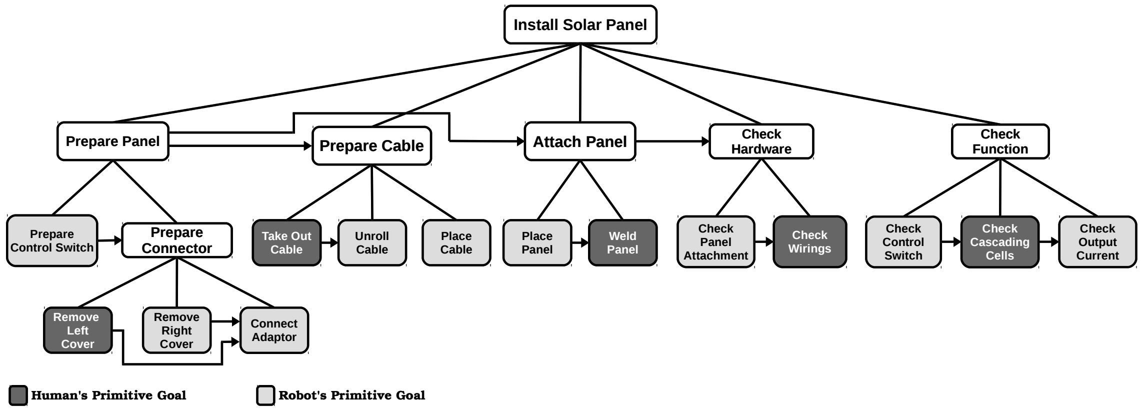

Figure 5.7: Collaboration structure used as the task model.

Environment and Tasks

The environment was set up in a laboratory and included the robot, the collaboration board on top of a desk, and the participant standing in front of the robot on the other side of the board (see Figure 5.10). One of the experimenters monitored the interactions using a live stream of a camera in a different room. The experimenter provided only the required perception, i.e., decision on success or failure of the tasks for the robot, through the entire time of the collaboration (see Section 5.3.2). We also had a supervisor, whose purpose was to provide help to the collaborators when requested after a task failure.

The tasks were defined based on the collaboration structure shown in Figure 5.7 and were executed in a turn-taking fashion by either of the collaborators[1]. For each task either the robot or the participant was responsible for picking up one of the corresponding pegs from their own inventory and placing it on the right spot which was colored and tagged the same as the associated peg. Some pegs and corresponding spots on the board had hidden magnets which prevented the pegs from standing upright. Any peg that fell over was considered a failed task.

[1]Figure 5.7 was not given to the participants.

Framework

The framework includes all of the mechanisms depicted as mental processes in Figure 5.6 along with the Mental State. The mental states shown in Figure 5.6 comprise the knowledge base required for all of the mechanisms in the overall model. The details about these mental processes and Mental State are described in Chapters 3 and 4. We use Disco as the basis of the Collaboration mechanism. Disco is the open-source successor to COLLAGEN [203, 204] which incorporates algorithms based on SharedPlans theory for discourse generation and interpretation. Disco is able to maintain a segmented interaction history, which facilitates the collaborative discourse between a human and a robot. In this user-study, the Collaboration mechanism uses a hierarchy of goals associated with tasks in the hierarchical task network structure depicted in Figure 5.7.

The Robot

We conducted our experiment with a KUKA Youbot (see Figure 5.10). The robot was stationary on top of a desk and was able to pick up and place available pegs corresponding to the robot's task. The robot was operated based on Robot Operating System (ROS – indigo) and was receiving commands through the ROS-bridge from our Affective Motivational Collaboration framework (see Figure 5.6). We provided a simple GUI using a touch-screen monitor (see Figure 5.9) to a) express the robot's positive, negative or neutral affective state through an emoticon, b) display the robot's utterances, c) control turn-taking process of the collaboration, and d) let the participants express (report) their positive, negative or neutral affective state for each turn. The GUI was identical in both affect-aware and affect-ignorant conditions (see Section 5.3.2). The robot used the MaryTTS[1] text-to-speech platform to provide corresponding speech for its utterances in English.

[1]http://mary.dfki.de/

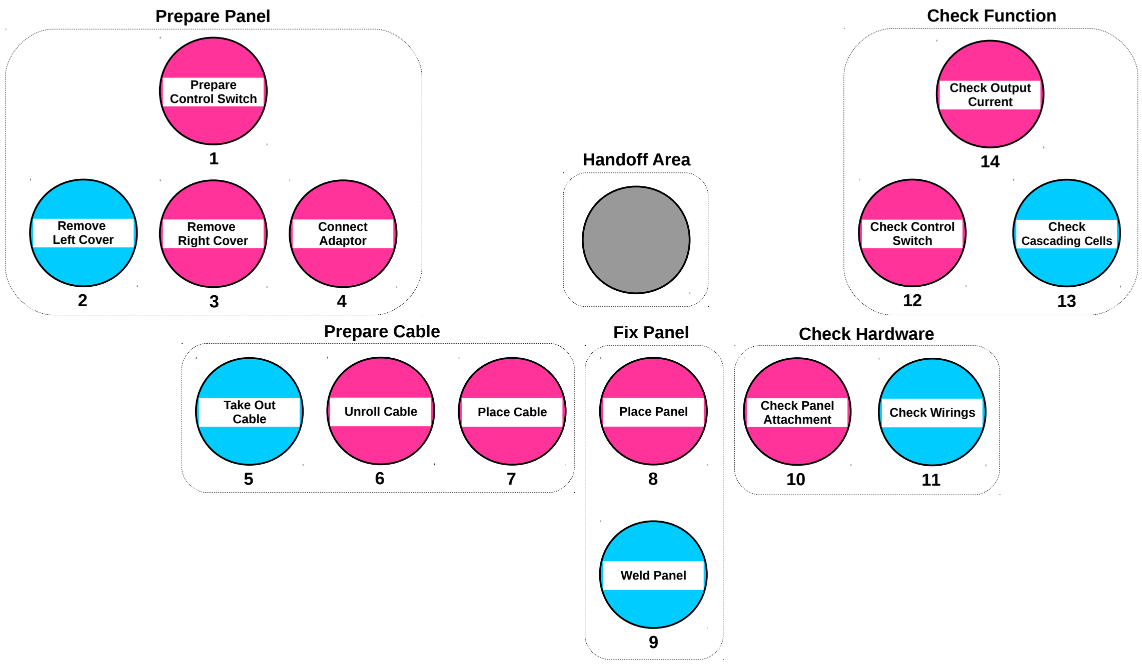

Figure 5.8: The layout of the available spots for the human and the robot to place their pegs during the collaboration.

Robot Controller

The robot controller is comprised of two major components: 1) ROS-bridge and 2) joint controller (see Figure 5.6). ROS-bridge[1] provides an API to ROS functionality for non-ROS programs which enables us to send action commands from our framework (implemented in JAVA) to the robot's joint controller. The joint controller receives action commands and translates them into actual joint and actuator commands and sends them to the robot (see Figure 5.10).

5.3.2 Experimental Design

Our scenario was based on a table top turn-taking game that we designed to simulate the installation of a solar panel. Participants collaborated one-on-one with our robot to complete all the given tasks required to install the solar panel. Each participant worked with the robot in two conditions, in a within subject study. Each primitive

[1] http://wiki.ros.org/rosbridge_suite

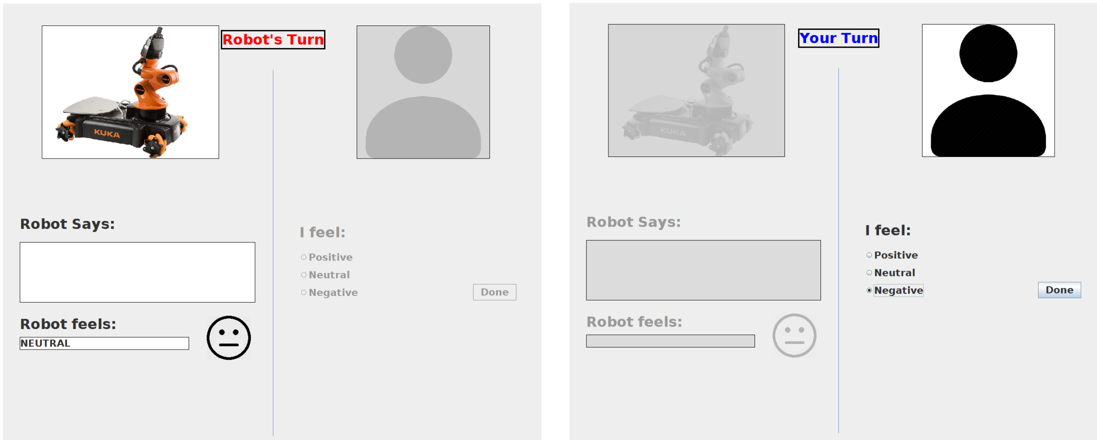

Figure 5.9: The Graphical User Interface (GUI) used during interaction.

task consisted of picking up and placing pegs on predefined spots on the board (see Figure 5.8). Each pick-and-place was associated with the robot's or the participant's task. The robot and the participants had their own unique primitive tasks that they had to accomplish in their own turns. The final goal of installing a solar panel required the robot and the participants to accomplish their own individual tasks. Failure of any task could create an impasse during the collaboration.

Interaction Paradigms

At the beginning of each collaboration the robot asked each participant to achieve the overall shared goal, i.e., "installing the solar panel". Then, before working towards a new goal, the robot informed the participant about the higher level non-primitive goal (e.g. Prepare Panel – see Figure 5.7) of which the primitives were going to be working towards. The same procedure was used by the robot if there was a decision to switch to another nonprimitive due to the failure of a task in achieving the current goal. After achieving a new primitive goal, the robot either informed the human that it would pursue the next goal, or it informed and passed the turn to the human to execute the next task with respect to the human's goal. In case of the human's turn, the robot waited for the human to do a task, then the wizard let the robot know whether the human's goal was achieved or not. Afterwards the robot made a decision about which goal to pursue and informed the human accordingly. There were two conditions of the robot: 1) affect-aware and 2) affect-ignorant. The same procedure was applied to both conditions. In the next section (i.e., Algorithmic Trace) we provide the algorithmic trace to show how goal management algorithm works in both affect-aware and affect-ignorant conditions.

The robot interacted via a) speech, b) the corresponding utterance on the screen, c) negative, positive and neutral expression of affective state through an emoticon on the screen. The robot used only neutral expression in the case of affect-ignorance. The interaction was controlled autonomously by the framework we discussed in Section 5.3.1 in both the affect-ignorant and the affect-aware cases. The reasoning about which task should be done and controlling the robot was entirely autonomous. Only the perception of the task failure or achievement by the robot or by the participant was done by a wizard monitoring the collaboration outside of the test area. The interaction was structured based on the same collaboration structure (see Figure 5.7) for both conditions. The robot used the same utterances in both conditions. In the affect-aware condition the robot used a different behavior in comparison with the affect-ignorant condition only if the participant was expressing a negative affective state in the event of a failure; i.e., the robot's utterances were identical in affect-ignorant and affect-aware cases if in the latter the participant reported (expressed) a positive or a neutral affective state.

Three different behaviors could be generated only in the affect-aware condition as a result of the Coping mechanism (planning, active coping, seeking social support for instrumental reasons, and mental disengagement coping strategies were involved to generate these three behaviors). These three behaviors were 1) mitigating the human's negative affective state and postponing its own task to help the human, 2) goal-management to switch to another goal which had lower cost with respect to the human's negative affective state, and 3) task delegation to the human to overcome the impasse. In each run, the human had two predetermined task failures, and the robot had one. If the human expressed negative affective state after the

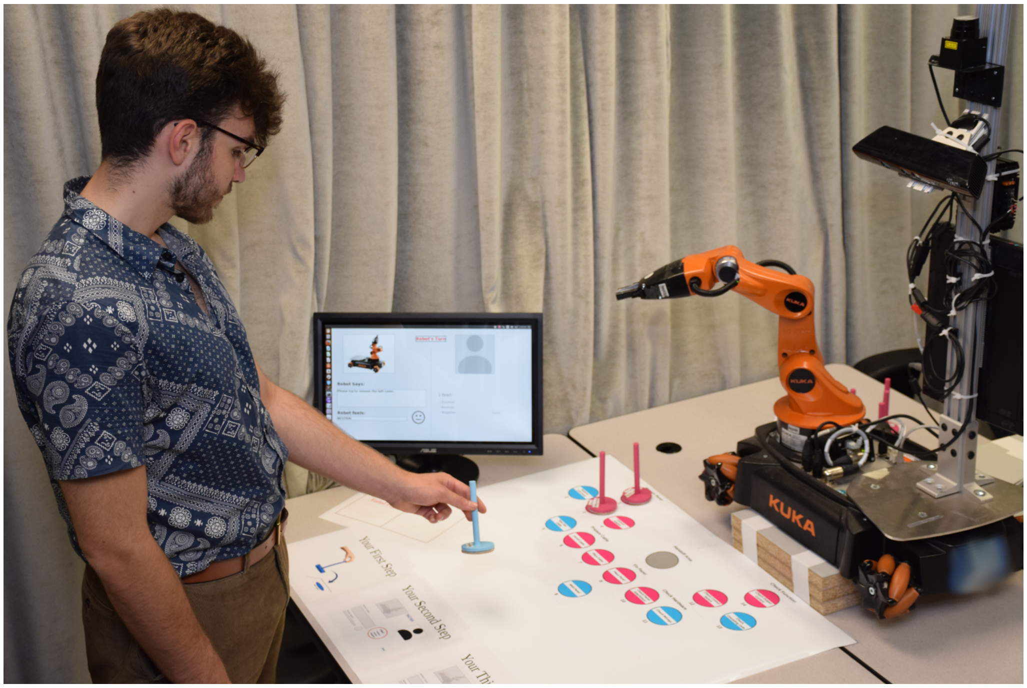

Figure 5.10: Experimental setup.

first human task failure, the robot responded by mitigating the human's negative affective state by saying "It was not your fault. I can help you with this task" and helping the human by providing a peg to fulfill the human's task. If the human expressed negative affective state after the second human task failure, the robot informed the human that they could proceed with another task to save time while simultaneously requesting a new peg (i.e., help) from the supervisor. If the human expressed negative affective state as a result of the robot's task failure, the robot requested help from the human (who had the correct peg). In the event that the human expressed positive or neutral affective state during these three failures, the robot behaved identically in the affect-ignorant and the affect-aware cases, by asking the supervisor for help.

Algorithmic Trace

In this section we provide an algorithmic trace for one of the three behavioral changes in our user study when the robot, besides acknowledging human's perceived negative affective state, activates a coping strategy called *mental disengagement*. As shown in Table 4.1, the mental disengagement strategy can be activated when the robot and the human feel neutral or negative, all three values of motives (see Section 4.6) have obtained low or medium negative values, and the robot evaluates the controllability of the corresponding goal of the event as uncontrollable one. As the result of activation of the mental disengagement strategy, our framework applies the goal management algorithm to lower the effect of the stressor which is the failure of a goal in the plan.

The following algorithmic trace shows how different mechanisms (see Chapter 4) in our framework are involved to generate proper behavior in response to the perceived goal-failure of the human in the affect-aware condition:

1. As a result of perceiving failure to achieve a goal by the human collaborator (i.e., "Take Out Cable" – See Figure 5.7), AMC framework uses the **Appraisal mechanism** to appraise this event. To be able to appraise the event, the Appriasal mechanism needs the current information of the collaboration structure.
2. Thus, the **Collaboration mechanism** provides the information required to appraise the current event. This information includes the status of the preconditions, postconditions, hierarchical and temporal constraints, inputs, outputs, status of the predecessors and contributing goals in the shared plan. All of this information appears as an element of Mental State, i.e., belief.
3. Then, the **Theory of Mind mechanism** provides the anticipated beliefs about the human collaborator's mental state based on reverse appraisal of the human's perceived affective state, i.e., negative (valence).
4. As a result, the **Appraisal mechanism**'s outcome will be *relevant, undesirable, unexpected* and *controllable.*
5. The **Motivation mechanism** uses the collaboration structure (Collaboration mechanism), anticipated beliefs of the human collaborator (Theory of Mind mechanism) and the outcome of the appraisal (Appraisal mechanism) to

compute the intensity of three motives (see Section 4.6), i.e., low or medium negative values for satisfaction, achievement, and external motives.

6. The **Coping mechanism** receives the values of the three motives and activates two coping strategies, i.e., Active Coping and Mental Disengagement, with respect to the conditions shown in Table 4.1. As a result of the activation of these strategies, first, active coping strategy forms a new intention to acknowledge human's negative affective state, and then, mental disengagement strategy uses the goal management algorithm to lower the effect of current stressor (goal failure) and overcome an impasse. The goal management algorithm uses the current collaboration structure and the human's perceived affective state to form a new intention to swtich to another goal which has the lowest cost (see Section 4.4), i.e., "Place Panel".
7. At the end, the **Action mechanism** receives two new intentions of acknowledging human's negative affective state and pursuing achievement of a new goal (i.e., Place Panel). As a result, the robot will say: "Don't worry! To manage the time let's switch to another task. We can come back and finish this later."

In affect-ignorant condition, AMC framework bypasses the **Appraisal, Theory of Mind, Motivation**, and **Coping mechanisms**. AMC framework forms a new intention based on the goal that the SharedPlans' collaborator manager, i.e., Disco, provides. In this condition the agent's decision is not influenced by the human's perceived negative affective state, even if the human reports a negative affective state. As a result, the robot asks the supervisor to come and provide help to overcome an impasse in response to the human's goal failure.

5.3.3 Hypotheses

The non/social functions of emotions impact a collaboration process. Human collaborators prefer to collaborate with others whose behaviors are influenced by these