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 affect to reveal their internal states in social contexts including collaboration [35]. Due to the existence of such expressions, robots' affect-awareness can improve the quality of collaboration in terms of humans' perception of performance and preferences. Hence, col-

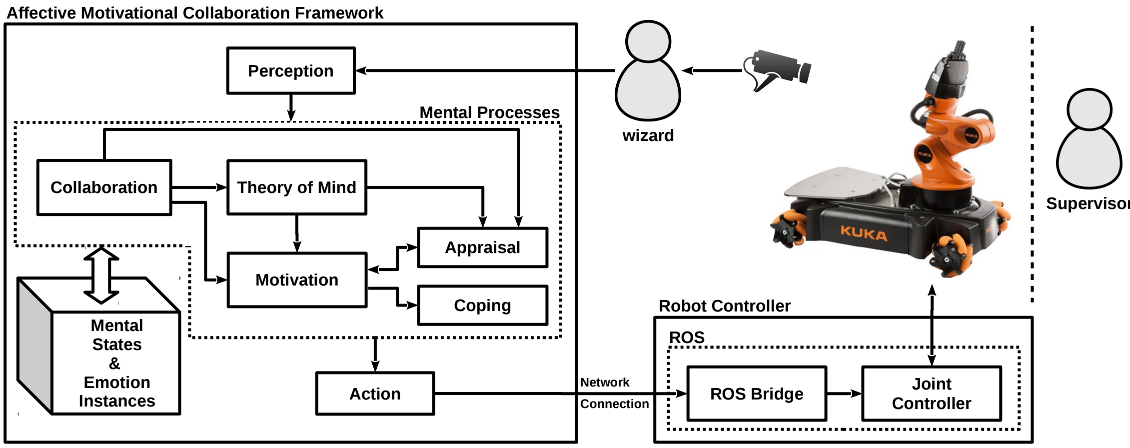

Figure 5.6: Experimental setup for end-to-end system evaluation.

laborative 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 affect awareness and the underlying affect-driven processes in human-robot collaboration. We examined how affect-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 the four main elements shown in Figure 5.6. The first element is the implementation of the Affective Motivational Collaboration framework (see left-side of Figure 5.6) as described in Chapter 4. In this user-study, the Collaboration mechanism in our framework uses a hierarchy of goals associated with tasks in the hierarchical task network structure. This goal-hierarchy provides three levels of goals, including: top-level goals, main subgoals, and primitive goals (see Figure 5.8). The second element was implemented to receive action commands from the framework and forward them to the robot to control joints and actuators (see Robot Controller in Figure 5.6). A wizard was the third element of this setting. The wizard did nothing except inform the robot/framework whether the current

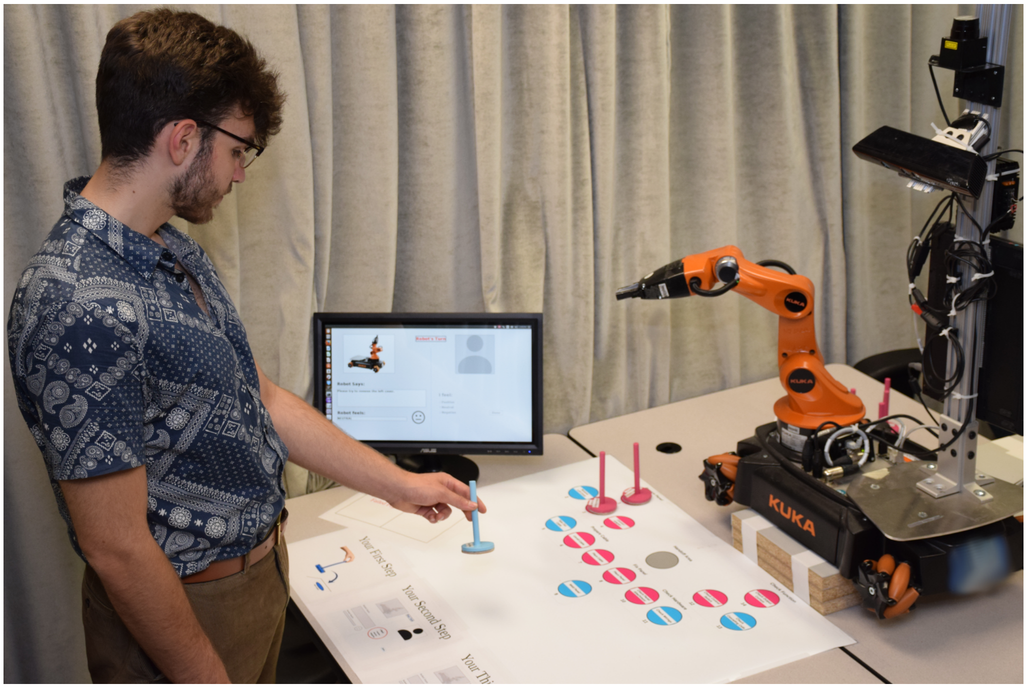

Figure 5.7: Experimental setup.

task performed by either the robot or the participant was achieved successfully. The wizard was completely invisible to the participants, and had no impact on the robot's behavior other than providing input regarding tasks' failure or success. The last element was the supervisor. The supervisor in affect-aware condition was providing the right peg to the robot or the human (see **Environment and Tasks** in this section) in case of a task failure, only when the human reported a neutral or positive affective state. The robot did not ask the supervisor to come and help if the human reported a negative affective state (see **Interaction Paradigm** in Section 5.3.2). In the affect-ignorant condition the robot always asked the supervisor to help and provide a correct peg irrespective of the human's reported affective state.

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 5.7). The wizard in Figure 5.6 monitored the

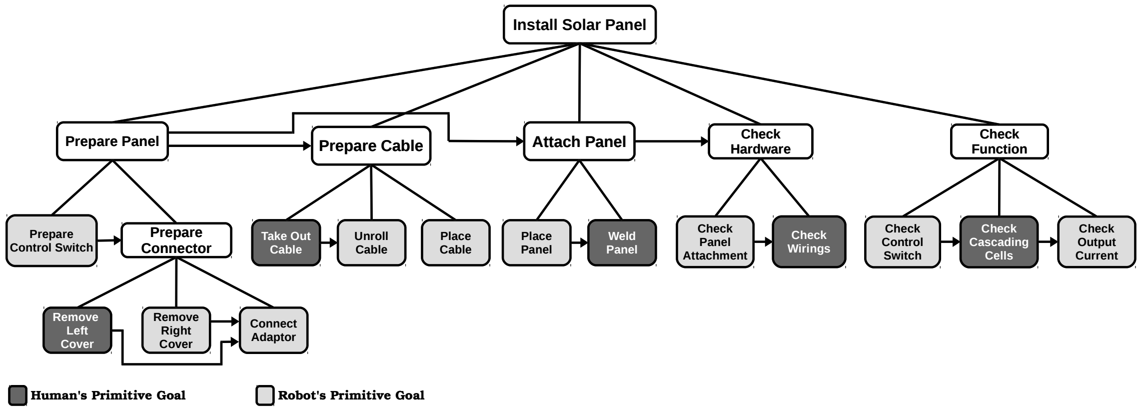

Figure 5.8: Collaboration structure used as the task model.

interactions using a live stream of a camera in a different room. The wizard 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.

The tasks were defined based on the collaboration structure shown in Figure 5.8 and were executed in a turn-taking fashion by each of the collaborators[1]. The collaborators used the task board displayed in Figure 5.9. 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 (see Appendix B).

The Robot

We conducted our experiment with a KUKA Youbot (see Figure 5.7). 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 distribution: 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 5.10) to a)

[1]Figure 5.8 was not given to the participants.

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 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.

Robot Controller

The robot controller is comprised of two major components: 1) ROS-bridge and 2) joint controller (see Figure 5.6). ROS-bridge[2] 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.

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 task consisted of picking up and placing pegs on predefined spots on the board (see Figure 5.9). 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 participants to accomplish all of their own individual tasks. Failure of any task would create an impasse during the collaboration.

[1] http://mary.dfki.de/
[2] http://wiki.ros.org/rosbridge_suite

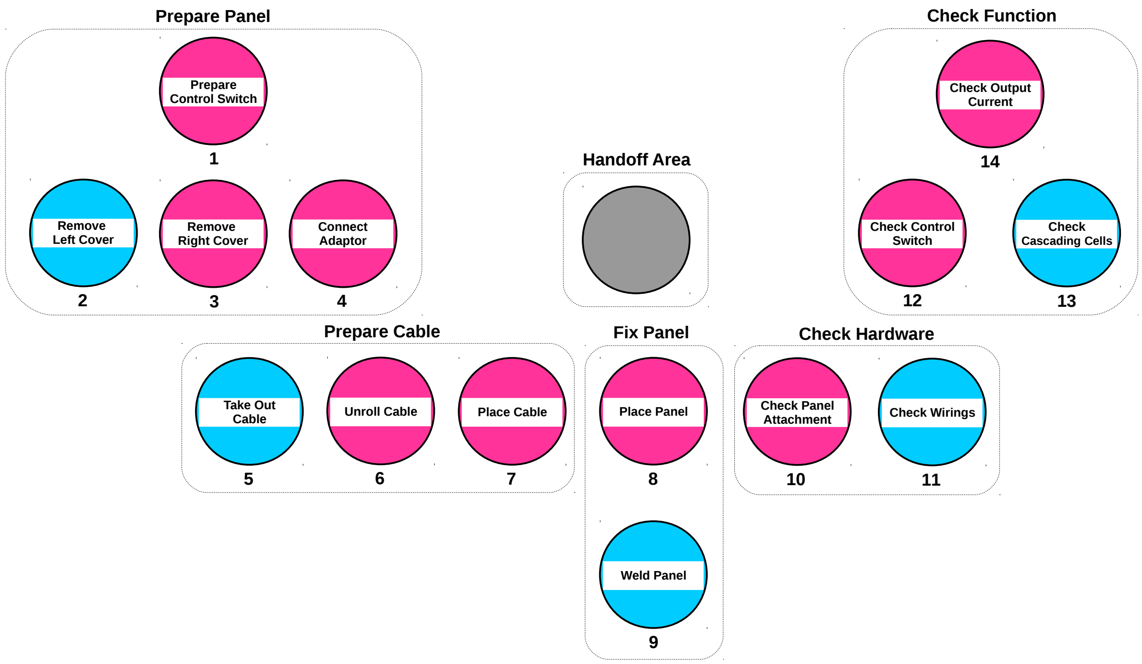

Figure 5.9: The tabletop layout of the available spots for the human and the robot to place their pegs during the collaboration.

Interaction Paradigm

At the beginning of each collaboration the robot asked the participant to achieve the overall shared goal, i.e., “installing the solar panel”. Then the robot informed the participant about the immediate parent non-primitive goal (e.g. Prepare Panel – see Figure 5.8) that the primitives are contributing to, before working towards a new sub 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 achieve a primitive goal, 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.

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

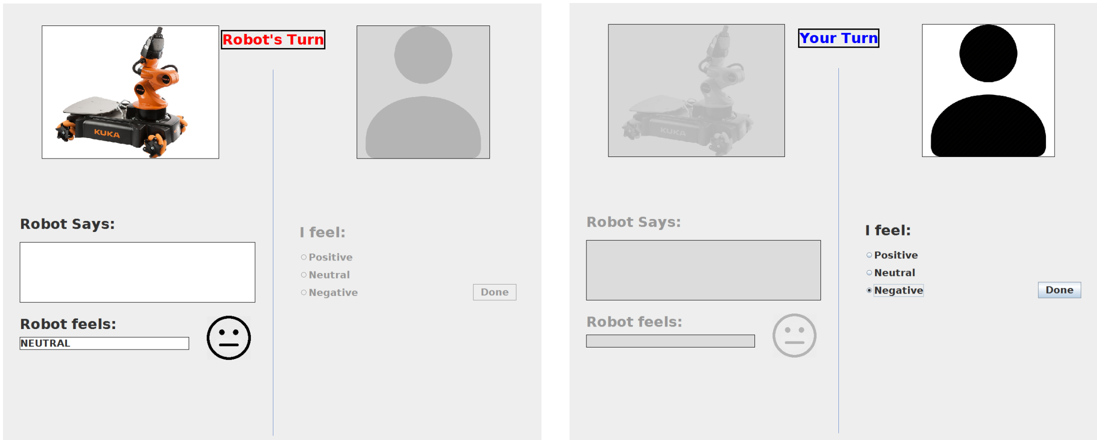

Figure 5.10: The Graphical User Interface (GUI) used during interaction.

on the screen. There were two conditions of the robot: 1) affect-aware and 2) affect-ignorant. The same interaction paradigm was used in both conditions. In each condition, the human had two predetermined task failures, and the robot had one. In the affect-aware condition we considered the impact of human's affective state on appraisal outcome and reciprocally on the processes influencing the collaboration structure, e.g., goal management. In the affect-ignorant condition we bypassed all of the mechanisms in the AMC framework except the Collaboration mechanism which was required to generate collaborative behaviors based on the shared plan.

The robot's behaviors were the same for both affect-aware and the affect-ignorant conditions when the human collaborator reported neutral or positive affective state. In these situations, for the affect-aware conditon the only coping strategy that could become activated was *Planning* strategy which was using Disco as the collaboration manager in our Collaboration mechanism. Using the collaboration manager as a result of the activation of the planning strategy in affect-aware condition caused the robot to generate exact same behavior as the affect-ignorant condition; since in the latter condition the mechanisms of the whole framework are bypassed and reduced to only Collaboration mechnism which generates behaviors based on Disco. The reasoning about which task should be done and controlling the robot was entirely autonomous under the above situation for both conditions. Therefore, in both the affect-ignorant and the affect-aware conditions, the robot responded by asking the supervisor for help. The interaction was structured based on the same collaboration structure (see Figure 5.8) for both conditions. Also, the robot's utterances were identical in affect-ignorant and affect-aware cases if in the latter the participant reported a positive or a neutral affective state.

The affect-aware and affect-ignorant conditions only differed in case of a robot's task failure or when human reported negative affect in response to failure of a task. In this situation, the affect-ignorant condition still used Disco to generate collaborative behaviors, and the robot used only the neutral expression using the emoticon. However, in the affect-aware all the mechanisms were involved to activate proper coping strategy in response to robot's task failure or human's perceived negative affective state. All other coping mechainsms (see Section 4.5) are designed to generate proper behavior in case of failure of a task, including proper positive, negative or neutral expression using the emoticon. We had three behavioral changes that could only happen in affect-aware condition and only when the human reported a negative affective state or when the robot failed. Thus, planning, active coping, seeking social support for instrumental reasons, and mental disengagement coping strategies were involved to generate these three behaviors. These three robot behaviors were:

1. Mitigating the human's negative affective state and postponing its own task to help the human. If the human expressed negative affective state after the 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.
2. Goal-management to switch to another goal which had lower cost with respect to the human's perceived negative affective state. 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.
3. Task delegation to the human to overcome the impasse. If the robot faced a

task failure (robot's negative affective state), the robot requested help from the human (who had the correct peg).

In the following section we provide the algorithmic trace to show how goal management algorithm works in both affect-aware and affect-ignorant conditions.

Algorithmic Trace

In this section we provide an algorithmic trace to clarify the difference between two conditions. This algorithmic trace is based on 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*. This situation occurred when the human collaborator failed to "take out cable", which was the second failure in our study. 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 5.8), 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 precon-

ditions, postconditions, hierarchical and temporal constraints, inputs, outputs, status of the predecessors and contributing goals in the shared plan. All of this information appears as elements of Mental State, i.e., beliefs.

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 affect.
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, 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, the 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**. The 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 functions of emotions depending on the context. We developed seven specific hypotheses regarding the positive influence of affect-awareness and the usefulness of emotion function during collaboration:

Hypothesis 1. Participants will feel closer to the affect-aware robot rather than the affect-ignorant robot.

Hypothesis 2. Participants will find the affect-aware robot to be more trustworthy than the affect-ignorant robot.

Hypothesis 3. Participants will find the affect-aware robot to have better performance in collaboration than the affect-ignorant robot.

Hypothesis 4. Participants will find the affect-aware robot to be more understanding of their feelings than the affect-ignorant robot.

Hypothesis 5. Participants will find the affect-aware robot to be more understanding of their goals than the affect-ignorant robot.

Hypothesis 6. Participants will feel more satisfied about the collaboration when working with the affect-aware robot rather than affect-ignorant robot.

Hypothesis 7. Participants will perceive higher level of mutual satisfaction with the affect-aware robot than affect-ignorant robot.