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Doctoral Thesis

On the Influence of Social Robots in Cognitive Multitasking and its Application

submitted by

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Abstract

The objective of the thesis was to clarify the influence of social robots on cognitive multitasking and its principles and to provide potential industrial applications.

In the thesis, the iCub robot, widely used in social interaction research, was used as a stimulus from social robots in the experiments. Also, I aimed to achieve broad applicability of the results by utilizing the Multi-Attribute task Battery (MATB) as a generalized cognitive multitasking that can measure reaction speed, tracking performance, and short-term memory tasks, rather than limiting the research to specific applications such as driving tasks for cars or airplanes.

However, since no system for simultaneously measuring the robot iCub's movements and human multitasking performance has existed to date, the first step in the research was to establish the system. Then, using the system developed, I conducted two types of experiments to clarify the objective of the thesis. Therefore, one of the novelties in the thesis is that it was the first to be able to evaluate the effects of a social robot on multitasking scenarios.

In the first experiment, I evaluated whether social robots influence cognitive task performance by comparing social robots that use social signals with nonsocial robots that do not. The study focused on the initial question of whether social robots could have the potential to have a positive impact on cognitive multitasking. From the results of the experiment, it was found that social robots tended to improve performance on a cognitive task requiring short-term memory and to make participants more relaxed on measures of skin conductance, compared to nonsocial robots.

The second experiment aimed to explore in depth the principles of how social robots affect human performance. Therefore, I set the research question of how social robots should behave depending on the type of task and evaluated the impact of different behavioral styles based on "vitality forms" advocated by Daniel Stern on cognitive multitasking. The study revealed new insights into how social robots should behave according to different task characteristics, as expected in real-world settings. My results revealed that participants performed better on cognitive tasks requiring short-term memory when they were with a gently behaving robot than when with a rudely behaving robot, and they also performed better on a continuous tracking task. In this experiment, I also analyzed the facial expressions in terms of arousal and valence of the participants and found that a gently behaving robot tended to make the participants' facial expressions more positive.

The results from the two experiments showed that when applying robots to help with cognitive multitasking, it is useful to use social robots and to change the way the social robots behave depending on the type of task that the human is performing.

In addition, since industrial applications of social robots are often limited by physical space constraints, I challenged the design of a novel social robot using only the head of the iCub, which is smaller and more flexible in placement than a full-bodied humanoid robot. In downsizing, omitting the torso from the iCub may result in a decrease in expressive capabilities and a weakening of the social presence of the robot. Therefore, I improved the design of the eyebrows based on the iCub head so that the robot head can achieve satisfactory communication ability. The novel soft-material eyebrows I have developed allow for continuous motion, different from the conventional iCub's LED eyebrows. This allows for detailed speed changes of eyebrows, which is an important factor in vitality forms.

The thesis results are valuable not only for research on the fundamental principles of social robots but also for opening up the possibility of applying social robots to non-robotic industries, such as automobiles and aircraft, which involve cognitive tasks. In addition, the precise shape and velocity changes of the soft material eyebrows developed in this study have enabled experiments on complex facial expressions such as joy, anger, sorrow, and pleasure that go beyond Ekman's simple definition of facial expression change and have opened up new possibilities for social robotics and social interaction research itself. Thus, my research is an important step forward in both scientific and industrial applications.

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Chapter 1

Introduction

1.1 Motivation

Humans communicate richly with explicit social signals such as verbal signals and implicit social signals such as gaze [1], tone of voice [2], facial expressions [2, 3], and gestures [4, 5]. Social signals are defined as communicative or informative signals that directly or indirectly provide information about "social facts": social interactions, social emotions, social attitudes, evaluations and stances, social relations, and social identities [6]. For the definition of social robots, Henschel et al. reviewed various previous studies[7]. For example, Mejia and Kajikawa summarized social robots as "robots as social partners" and "human factors and ergonomics in human-robot interaction" [8]. Sarrica and colleagues defined social robots are physically embodied agents that have some (or full) autonomy and engage in social interactions with humans, by communicating, cooperating, and making decisions [9]. de Graaf, Allouch, and van Dijk evaluated users' perspectives on the characteristics of social human-robot interaction and identified the most prominent factor was (1) the capability of two-way interaction, (2) displaying thoughts and feelings (3) being socially aware of their environment (4) providing social support by being there for them (like their friends) and (5) demonstrating autonomy [10]. All of these researchers have attempted to define social robots, and what they all have in common is that they are robots that communicate by utilizing social signals. Therefore in the following, I refer to robots that use social signals as "social robots" and robots that do not use social signals as "nonsocial robots". By making it possible for robots to recognize and control the social signals that humans use in their daily lives, communication between humans and robots becomes more effective, which leads people to recognize robots as social beings and to perceive social presence in robots [11, 12, 13].

Most of the previous human-robot interaction(HRI) studies have focused on collaboration when humans and robots perform tasks in turn. G. Hoffman *et al.* analyzed a collaborative task in terms of fluency and found that idle times of each human and robot were correlated with subjective fluency in a task in which a participant and a robot carried objects in a bucket relay way on a game screen [14]. J. Okimoto *et al.* found that audio cues help to predict the robot's actions in a task in which humans and robots pick objects in turns [15]. From the perspective of social signals, Ivaldi *et al.* evaluated the impact of a robot's gaze on its human partner in a building object task using a humanoid robot iCub [16]. However in contrast to these tasks, many real-life collaboration tasks are not clearly separated and need to be performed simultaneously and collaboratively across multiple cognitive tasks.

Turning to the automotive industry, they are developing vehicles that can operate with level 3, 4, or 5 autonomous driving [17] in addition to conventional driver assistance functions such as lane keeping [18], adaptive cruise control [19], and emergency braking [20] in order to reduce the number of vehicle accidents. One of the reasons behind the development of autonomous driving is the need to reduce the number of driving failures caused by the high cognitive load originally imposed on drivers [21, 22, 23], as driving tasks are complex cognitive multitasking that involves dealing with various objects simultaneously, such as traffic signals, pedestrians, lanes, and surrounding vehicles. However, even with the advance of autonomous vehicles [24, 25], there can still be situations in which the drivers themselves want to drive the vehicles [26], or in which autonomous vehicles encounter unknown situations [27] that require collaborative driving with the drivers [28]. Therefore, the automotive industry requires ways to achieve efficient and smooth assistance and collaboration with drivers.

With these backgrounds, the automotive industry in recent years has been promoting research and development of social robots to support communication in cars, such as PIVO2 [29], HANA [30] and Nomi [31], with the concept of a conversation partner for the driver. In the academic field, N. Foen *et al.* [32] developed AIDA for the purpose of supporting components not directly related to driving. The robot is designed to express emotions through its eyes on a smartphone, neck joints, and voice. A subsequent study by K. Williams *et al.* showed that an AIDA which allows for the expression of emotions with the neck, is less burdensome than an eye-only AIDA [33, 34]. Additionally, NAMIDA, developed by N. Karatas *et al.*, was designed to communicate with drivers with three robots that have only two eyes for each of them [35]. A unique feature of the robots is that they are designed to engage in conversations between the robots so that a driver does not necessarily have to join the conversation. Thereby, it was found that the workload related to communication was reduced in comparison to the case of a single NAMIDA agent. Also, Wang et al. found that when the agent has a physical body as a humanoid robot and interacts with the driver in a conversational style, the agent has more warmth and likability than an agent that has no physical body and specializes in providing information, and it focuses the driver's attention on the agent [36].

In terms of evaluating driving performance, Tanaka *et al.* created a passenger robot, and their experiments using a driving simulator revealed that driving with the robot resulted in a much slower average driving speed than driving without the robot [37]. However, as few other studies have evaluated the impact on driving performance, research on social robots to provide effective driving support is becoming increasingly desirable.

Even in the field of general cognitive tasks, a few studies have been conducted in HRI research. Spatola *et al.* found the presence of social robot (compared with isolation) improved standard Stroop performance and response conflict resolution (a specific component of Stroop performance) [38]. In addition, Sgrigoroaie *et al.* evaluated performance in the Stroop test task in a human-robot interaction (HRI) scenario using a social robot called Tiago [39]. They compared a robot that encouraged impatience and a robot that encouraged relaxing. From the study, they found that the former robot that constantly moved beside participants turned around, and said impatient words to the participants, such as "hurry up," causing higher mental workloads to the participants than the latter robot that did not move and encouraged the participant to relax, think carefully, and not worry. Also, Spatola *et al.* found the presence of a social robot improved selective attention performance compared to the presence of a nonsocial robot in the Eriksen Flanker task [40].

1.2 Research objective

From the motivation, the research objectives of the thesis are to clarify the impact of social robots on cognitive multitasking and their principles and to provide a possible way through the development of hardware to apply social robots to industries such as automotive.

1.3 Thesis outline

First, in chapter 2, I describe the MATB-YARP system developed to evaluate "the impact of social robots on cognitive tasks," which is the centerpiece of the thesis. The MATB-YARP is a battery of cognitive tasks developed to work with YARP [41], the robot middleware used in the iCub. Thereby, I was able to construct a new experimental environment to verify the basic principles of interaction with a social robot during cognitive tasks.

Next, in chapter 3, I evaluated the effects of social robots on cognitive tasks using the MATB-YARP, which was constructed in chapter 2. In the experiment, I compared social and nonsocial robots. I found that the social robot improved performance on a cognitively demanding task that required short-term memory and had a relaxing effect on participants. In contrast, the nonsocial robot's instructions improved the participants' performance on a simple reactive task.

Furthermore, in chapter 4, I evaluated the effects of different vitality forms of social robots on cognitive multitasking in order to further deepen the impact of social robots on cognitive tasks. Similarly in chapter 3, I used the MATB-YARP as cognitive tasks. The results showed that the social robot behaving in gentle vitality forms improved better on the cognitively demanding task, which requires short-term memory, and on the tracking task, which requires continuous concentration, compared to the social robot behaving in rude vitality forms. In addition, the gentle social robot relaxed the participants during the experiment and made their facial expressions more positive. Based on the study in chapter 4, I found that it is important to express vitality forms by changes in the velocity of behaviors.

In chapter 5, I aimed to develop novel hardware that can express vitality forms in a car and an aircraft with the experimental results in chapter 3 and 4. However, it is not realistic to place a full-body iCub [42, 43] in the cockpit of a car or airplane as it is in terms of spatial constraints. Therefore, I developed novel hardware based on the idea of placing only a robot head as one of the solutions. On the other hand, a robot head without a torso is unable to express vitality forms using the upper limbs, as described in chapter 4. Conversely, if the conventional iCub robot head is utilized as it is, it is not enough to express the differences in vitality forms because the facial expressions are controlled by discrete LEDs and that cannot control the velocities. Therefore, by changing the eyebrows from conventional LED eyebrows to wire-driven elastic eyebrows, I improved the robot head's capability of expressing vitality forms [44, 45, 46] by continuously changing their shapes and speeds and its social presence [11, 12, 13] through richer expression. Thus, the robot head can facilitate the improvement of cognitive tasks in a car and aircraft, i.e., driving tasks and piloting performance.

Finally, in chapter 6, I discuss the overall research in the thesis based on the results of the experiments and the findings obtained through the development of the novel social robot head and conclude.

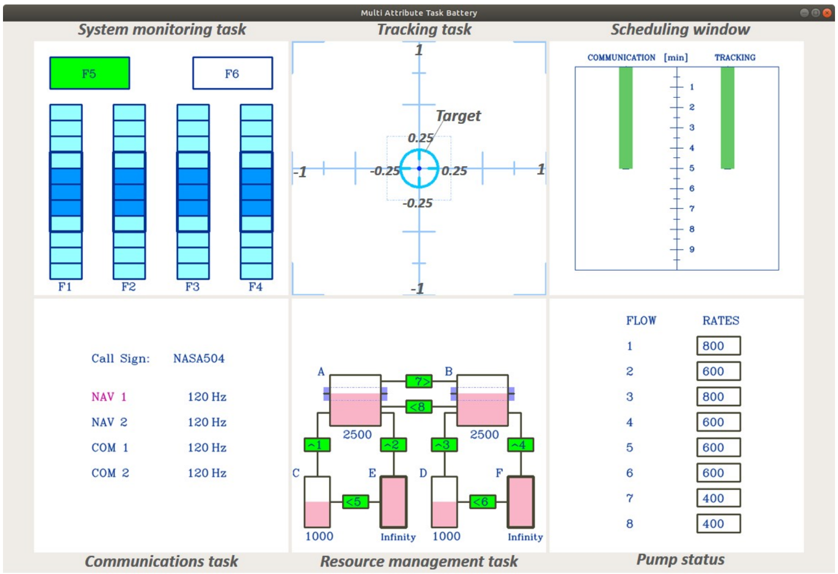
Chapter 2

Development of measurement system for collaborative cognitive tasks with robots

2.1 Multi-Attribute Task Battery (MATB) and relevant studies

The Multi-Attribute Task Battery (MATB) is a battery of standardized and generalized cognitive tasks that replicates aircraft operations, originally developed by NASA, to assess operator performance and workload in realistic tasks [47]. Later on, the MATB-II (Revised Multi-Attribute Task Battery) [48] was developed. They have been selected as a measuring tool in other studies [49, 50, 51] that share the need to measure operator performance and workload in simultaneous generic multi-tasks for the context.

The MATB is based on pilots' tasks, including the system monitoring task, which is a simple visual reactive task, the tracking task, which is a continuously focusing task, and the communications task is a cognitively demanding task that involves short-term memory of spoken instructions and execution. Since each task is generalized, it has been used in basic research on not only aviation research but also automotive research [52, 53]. Zhang *et al.* showed that the reaction time of the system monitoring task in the MATB was significantly correlated with the maximum speed of driving [52]. Also, Takae *et al.* showed that the effects of alcohol were more likely to appear in the tracking task of the MATB which is similar to lane keeping in driving [53]. The airplane pilot task and the car driving task are tied to each other in research [54, 55]. Hu *et al.* reviewed noninvasive methods for measuring sleepiness and mental fatigue in both car driving tasks and airplane pilot tasks [55]. Moreover, Borghini *et al.* reviewed the literature linking car driving tasks to aircraft piloting tasks and showed that it exists a coherent sequence of changes for neurophysiological measurements (electroencephalography: EEG, electrooculography EOG;



Call Sign: NASA504

NAV 1 120 Hz
NAV 2 120 Hz
COM 1 120 Hz
COM 2 120 Hz

FLOW	RATES
1	800
2	600
3	800
4	600
5	600
6	600
7	400
8	400

Figure 2.1: Display of the MATB-YARP, which consists of multiple tasks.

heart rate: HR) during the transition from normal drive, high mental workload and eventually mental fatigue and drowsiness. [54]. Thus, utilizing the MATB created based on the pilot task as basic research for cognitive tasks is beneficial from the perspective of both driving a car and piloting an airplane. However, in the HRI research, it is difficult to apply the MATB-II, the latest version officially released by National Aeronautics and Space Administration (NASA), to the HRI research since it is programmed in Microsoft Quick BASIC 4.5 and released as a compiled package, which does not allow to exchange the internal information with the iCub used in the thesis.

2.2 a novel MATB that can be linked to robot behaviors

Therefore, I developed the MATB-YARP (Fig. 2.1), which is a variation of the MATB for the thesis(2.1). The MATB-YARP can communicate through YARP (Yet Another Robot Platform) [41], allowing a complete controllable synchronization between the humanoid robot iCub robot and the task events. Like the MATB and MATB-II tasks, MATB-YARP consists of four tasks: the system monitoring task, the tracking task, the communications task, and the resource management task. Here in the thesis, I only adopted three tasks, the system monitoring task, the tracking task, and the communications task, since the resource management task is too difficult and has too much impact on the other tasks. For this reason, the resource management task was also developed in MATB-YARP, but I omitted its description in the thesis.

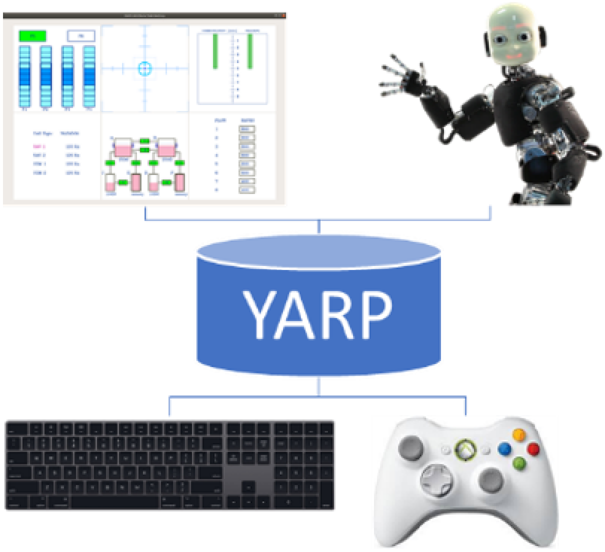


Figure 2.2: System architecture of MATB-YARP, robot, controller, and keyboard.

2.2.1 System architecture of MATB-YARP and an iCub robot

As shown in Figure 2.2, the newly developed MATB-YARP is connected to one of the robot middleware, YARP. YARP is capable of synchronously executing and recording signals not only on robots but also among connected computers. Therefore, information from iCubs, a controller, and a keyboard connected to the network of YARP can be managed all together. From the system through YARP, the iCub can now run in conjunction with MATB-YARP events, making it possible to experiment with a combination of cognitive tasks and HRI scenarios.

2.2.2 The system monitoring task

The system monitoring task is a simple reactive task, measuring reaction time based on visual information, which is displayed in the upper left window of figure 2.1. This task consists of visual events with four indicator lights and two warning lights. The participants must press the F5 key when the top-left box labeled F5 changes from green to white and press the F6 key when the top-right box labeled F6 changes from white to red. Pressing each key will return each key to its original color. Each of the four lower indicator lights is labeled F1 through F4, and each indicator moves randomly within the default frame indicated by the blue box while no event has occurred. When an indicator goes outside of the blue box, pressing the predefined key on F1 through F4 will cause the indicator to return within the default range indicated by the blue box.

2.2.3 The tracking task

The tracking task is a continuous compensatory task based on visual information, which is displayed in the upper center window of figure 2.1. In this task, participants use a joystick to keep the target center. The target moves randomly in the $x(-1.0 \text{ to } 1.0)$ and $y(-1.0 \text{ to } 1.0)$ directions on each sample (e.g. 30Hz) according to a Gaussian distribution (e.g. σ = 0.008, μ = 0). Participants can move the target in the direction of the joystick's tilt. In addition, participants can check how long the tracking task lasts by checking the gauge on the right side of the scheduling window, which is displayed in the upper right window of figure 2.1. The gauge decreases as time passes.

2.2.4 The communications task

The communications task is a task to perform multiple key operations based on auditory information, which is displayed in the bottom left window of figure 2.1. This task requires the participant to adjust the radio frequencies of predetermined channels according to voice instructions from an air traffic control. The participant needs to follow instructions from the air traffic control.When the controller instructs the participant to adjust a radio frequency, the participant needs to select the channel (NAV1, NAV2, COM1, or COM2) using the cursor keys on a keyboard $\uparrow$ or $\downarrow$, move to the frequency change box using the key $\rightarrow$, and adjust the radio frequency by using the keys $\uparrow$ or $\downarrow$. The instructions stream says "*Change NAV1 (NAV2, COM1, COM2) to* X Hz" in Italian. During the task, participants can check how long the communications task lasts from the gauge on the left side of the scheduling window, which is displayed in the upper right window of figure 2.1. The gauge decreases as time passes.

2.3 Conclusion

In order to proceed with research on cognitive multitasking at HRI, I developed the MATB-YARP and constructed an environment for experiments and data collection. In chapters 3 and 4, experiments will be conducted using the measurement system.

Chapter 3

Influence of social robots on cognitive multitasking

3.1 Introduction

In chapter 5, I develop novel hardware with highly expressive facial expressions to support cognitive tasks. In this chapter, I explain one of the reasons for its development: the impact of the social robot on cognitive tasks. In the experiment, the system described in chapter 2 is utilized.

Traditionally, collaborative tasks between humans and machines or arms-type industrial robots have been studied [56, 57]; however, robots that can be perceived as social beings (social robots) have been found to have social facilitation effects [58] on humans due to their social presence, and research on collaboration with social robots has been attracting attention in the robotics research. For example, human performance in several kinds of tasks was improved when they were monitored by the robot Flobi, as well as when they were monitored by a human, compared to when no one was monitoring them [59]. However, the context of social facilitation is complicated, and as with person-to-person influences, it is essential to conduct research under different conditions to achieve better performance of collaborative teams with social robots.

Evaluating performance while a person is being monitored by a robot is close to a form of relationship like that between a teacher and a student or a coach and an athlete. On the other hand, when a team performs the same tasks, such as the relationship between a driver and a front-seat passenger in a car, a pilot and a co-pilot in an airline pilot, or walking somewhere with friends, the relationships are different from that of monitoring. It is rather a collaborative relationship in which people face the same direction, and so far, there has been little study of the social facilitation with the robot in this relationship.

Therefore in this chapter, the study aims to explore the applicability of social robots in situations where multiple social beings collaborate in cognitive multitasking, such as driving a car or piloting an aircraft, where they need to observe multiple objects simultaneously.

3.2 The experimental design

This section describes the research hypothesis and design based on relevant studies and describes the tasks assigned to participants.

3.2.1 Relevant studies

3.2.1.1 Social facilitation

Back in social facilitation research, I found the first experiment on pacing and competition conducted by Triplett in 1898 [60]. Triplett noted that competitive cyclists recorded faster times when they raced against each other than when they raced alone. The study observed that the fastest times came from cyclists who raced against each other, and the slowest times came from cyclists who raced against the clock without a pacemaker. Later, the term "social facilitation" was used for the first time by Allport, who found that in a variety of tasks, responses were enhanced when others were present rather than when the task was performed alone [58]. Early research on social facilitation focused on the other-competition paradigm, but later research has included the passively observed paradigm [61]. Zajonc's drive theory asserts that the mere presence of others automatically and unconditionally causes an organism to experience general drive (arousal) [62]. The study marks an important milestone in the research of social facilitation. However, social facilitation has subsequently been studied in a variety of tasks and has been found to improve performance in simple tasks but to decrease performance in complex tasks (e.g., writing a report with prolonged concentration). Also, these are dependent on the type of tasks, complexity, evaluation context, competing/monitored, or type of relationship. Therefore, it is crucial to consider how social facilitation works, taking into account a variety of factors.

3.2.1.2 Social facilitation from robots

Social facilitation effects have also been observed to occur between humans and social robots, and Bartneck found that participants scored higher in the condition where they were monitored by a 3D robot agent compared to the condition where they were monitored by a projected agent on a screen [63]. The result was explained in terms of social facilitation, where it was considered that the 3D robot agent had a stronger social facilitation effect than the 2D agent, which encouraged the participants to expend more effort. Spatola *et al.* also found a positive social facilitation effect in the Stroop test only when anthropomorphic speculation driven by prior verbal interaction with the robot was triggered, but there is no effect when no prior interaction is performed. [38]. Also, Spatola *et al.* found the social facilitation effect also in the Eriksen Flanker task [40]. In addition, Sgrigoroaie *et al.* evaluated performance in the Stroop test task in human-robot interaction (HRI) scenario using a social robot called Tiago [39]. They compared a robot that encouraged impatience and a robot that encouraged relaxing. From the study, they found that the former robot that constantly moved beside participants, turned around, and said impatient words to the participants, such as "hurry up," caused higher mental workload to the participants than the latter robot that did not move and encouraged the participant to relax, think carefully, and not worry. For the analysis of mental workload, they evaluated the accumulated galvanic skin response (AccGSR) [64, 65], which is the sum of galvanic skin response (GSR) values over the task time. From the analysis, it was shown that the robot that encouraged relaxing had a lower value of AccGSR than the robot that encouraged impatience. However, there was no significant difference in the performance of the Stroop test between the two conditions. In the study, it is possible that both conditions aroused the participants' cognition in the same way since both robots spoke every 4 seconds during the task. On the other hand, when compared to the no-robot condition, both conditions showed a performance improvement.

3.2.1.3 Robot anxiety

If robots are seen as social beings rather than machines, and if they can have a social facilitation effect, people may unconsciously perceive them as intelligent beings. This could raise expectations about the conversational capabilities of robots, but also raise doubts. To evaluate such doubts about the conversational abilities and behaviors of robots, Nomura *et al.* created a questionnaire, the Robot Anxiety Scale (RAS) [66, 67]. Using the RAS questionnaire, Zlotowski *et al.* found that differences in robot attitudes affect anxiety towards the robots [68]. In the study, a robot with a positive attitude is less likely to cause anxiety toward the robot than a robot with a negative attitude, and the degree of anxiety depends on the robot's appearance.

3.2.2 Hypotheses

Based on the previous studies, in particular, (1) that social facilitation affects performance improvement or deterioration, (2) that robots encouraging humans to relax reduce mental workload more than robots making human inpatient robots, and (3) that robots with positive attitudes reduce anxiety towards robots than robots with negative attitudes, I propose the following three hypotheses about cognitive multitasking:

- Hypothesis 1 (H1).
  Presence of a social robot affect task performance in a cognitive task with no direct advice.

- Hypothesis 2 (H2).
  Presence of a social robot reduce mental workload.
- Hypothesis 3 (H3).
  Interacting with a social robot decreases anxiety towards the robot.

3.2.3 Study design

To compare the effects of the robot's different communication styles, I defined two different experimental conditions. In the social condition, the robot displays social signals such as pointing behavior, recognition of the participant, and mutual gaze. In the nonsocial condition, the robot executes predefined actions at predefined timings, not respecting rules of social interaction (e.g. mutual gaze patterns [69], recognition of the other individuals [70]). Fig. 3.1 describes the experimental setting. All experiments were performed with the humanoid robot, iCub [42, 43], whose design and control infrastructure allows to reproduce both human-like (resulting from specific cognitive models of human-human interaction) and non-human-like coordinated movements by triggering different motor control strategies. The participants performed the MATB-YARP task (see section 3.2.5) which is a task battery that replicates several types of cognitive tasks that humans face when piloting an aircraft. The participants interacted with the MATB-YARP task for 5 minutes. The humanoid robot iCub (see section 3.2.6) played a simple role of indicating the start and the end of the task with different sentences for each condition and condition-specific body movements, including the torso and head movements as interactive behaviors during the whole MATB-YARP task. In particular, the robot provided advice by different pointing and gazing behaviors for each condition as well as different communicative behaviors towards the participant (explained in detail in the section 3.2.6). All participants answered a pre and post-questionnaire(see section 3.2.7).

3.2.4 Participants

I recruited 30 native Italian speakers (23 to 69 years old, M=31.4, SD=86.9) from the Italian Institute of Technology (IIT) and assigned 15 (6 female, 9 male) to the social condition and 15 (6 female, 9 male) to the nonsocial condition to mitigate concerns about bias during recruitment. All participants volunteered to join the experiment and did not receive financial compensation. The majority of the participants were familiar with the iCub robot and had completed at least undergraduate education. Each participant signed an informed consent form approved by the IIT ethical committee. The participants all agreed to the camera and microphone recordings during the experiment and the usage of the data for scientific purposes. The research conformed to the ethical standards laid down in the 1964 Declaration of Helsinki, which protects research participants, and was approved by the Liguria Region's local ethical committee in Italy (n. 222REG2015).

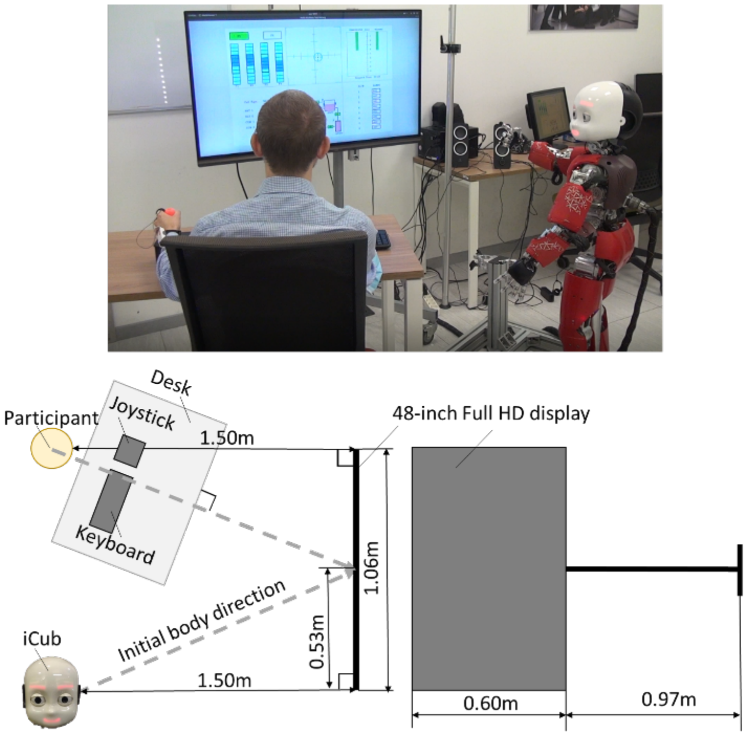


Figure 3.1: The experimental layout, showing the position of the participant, the iCub robot, as well as the recording devices.

3.2.5 Cognitive tasks (The MATB-YARP)

I developed MATB-YARP (see section 2.2), which can communicate through YARP (Yet Another Robot Platform) [41], allowing a complete controllable synchronization between the humanoid robot iCub robot and the task events.

Like the MATB and MATB-II tasks, MATB-YARP consists of four tasks: the system monitoring task, the tracking task, the communications task, and the resource management task. Here, I adopted three tasks, the system monitoring task, the tracking task, and the communications task. In the study, events on the system monitoring task and the communications task occurred in the timing shown in Fig. 3.2.

In the tracking task, the target moves randomly in the $x(-1.0 \text{ to } 1.0)$ and $y(-1.0 \text{ to } 1.0)$ directions on each sample (30Hz) according to a Gaussian distribution ($\sigma = 0.008$, $\mu = 0$ in this experiment). I designed the parameters to ensure that the target is controlled within the square while no other task events are occurring and that it is sometimes not possible to stay within the square while other task events are occurring. In the experiment, participants were encouraged to keep inside the small square ($-0.25 < x < 0.25, -0.25 < y < 0.25$) around the center. The tracking task is executed continuously from the beginning to the end of the 5-minute period in which MATB-YARP is performed. In the study, the average distances were measured every 20 seconds from the beginning of the task.

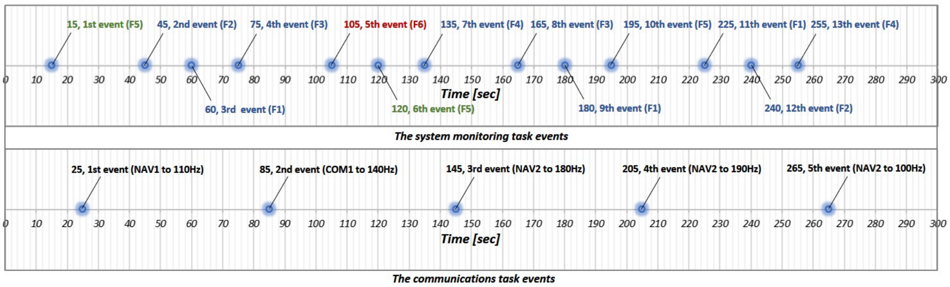


Figure 3.2: Outline of the MATB events for both the system monitoring task (first row) and the communications task (second row). The blue dots denote the timings and the expected inputs from the participants.

3.2.6 Stimuli (Interaction from robot)

The iCub interacts through physical movements and speech before, during, and after the MATB-YARP exercise. The robot behaviors are based on a finite state machine shown in Fig. 3.3. The robot control strategy transitions among four states: S_0 (Idle state), S_1 (system monitoring event state), S_2 (Wrong key pressed state), and S_3 (Target untracked state). The transition between states is triggered by events in the MATB-YARP, and by specific interaction input from the participant. The tracking task and the system monitoring task in MATB-YARP task are supported by the robot that addresses the participant with relevant suggestions. On the other hand, there is no robot state transition associated with the communications task so that the advice from the robot does not conflict with guidance from the air traffic control. The humanoid robot's behaviors are specific to the condition in which the participant is recruited. In the social condition, the robot advises with specific social signals widely accepted as typical of humanoid partners:

- social facial expressions: the humanoid robot iCub provides feedback on the tasks by changing its facial expressions with the led lights behind its face cover. In situations where the participants make a mistake the led facial expression changes to negative in less than 1 second.
- social gestures: the humanoid robot iCub performs coordinated whole-body movements that have a specific and explicit communicative meaning. In particular, both the arms move under the control of a position controller that operates in joint space to replicate always the same stimulation for all the participants. The movements are specifically designed to minimize the jerk and thus look smooth, natural, and human-like.

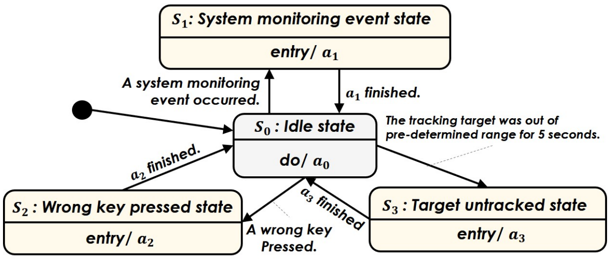


Figure 3.3: Finite state machine representing the flow of the interaction states with the iCub robot (see section 3.2.6.

- social gazing: the humanoid robot iCub detects autonomously the participant's face and the robot relocates the fixation point (estimated in 3D from extrinsic and intrinsic parameters of the camera in the robot's eyes) at the center of the participant's face with a natural and smooth saccadic eye and head movement.

In the nonsocial condition, the robot advises with different signals that do not respect the models of social cognition:

- nonsocial facial expressions: The humanoid robot iCub consistently remains expressionless during the experiment.
- nonsocial body motions: The humanoid robot iCub repeats a specific torso motion in a time transition without linking it to task events.
- nonsocial gazing: The humanoid robot iCub moves its fixation point by smoothly controlling the movements of its head and eyes, but the fixation point is not placed on the participant's face, but moves over the participant's body and never makes eye contact with the participant.

3.2.6.1 The social condition

Before starting the tasks, the robot interacts with participants with the following sentences that show social connotation since the sentences show social behavior that respects social models of interaction commonly identified in human-human interaction: 1) Speak, "*Look me in the eyes*" (in Italian) and make eye contact with the participant. 2) Speak, "*I inform you amicably that I am about to begin the experiment*" (in Italian) with open arms to the participant. 3) Bend both arms and speak "*Come on, let's start the experiment! I am here for you*" (in Italian) and smile at the participant.

After the tasks have started, the robot continuously transitions among the four states shown in Fig. 3.3. In S_0, the robot monitors the tasks in the display randomly(a_0). In S_1, S_2, and S_3, the robot advises with speech, saying "*Press F1(F2, F3, F4, F5 or F6), please*" (in Italian), "*If I can help you, you pressed the wrong key,*" (in Italian), and "*Sorry again, you have to correct your trajectory. Please be careful*" (in Italian) in addition to facial expressions and gestures (a_1, a_2, a_3). Also, the humanoid robot changes facial expressions by manipulating the pattern of LED activation under the face cover according to conventions of human-human social interaction [71]. Concerning the robot's behavior not directed to the human partner, the robot looks at the tasks on the monitor. To make it more realistic, the robot keeps selecting specific and realistic 3D locations on the monitor in a cycle. The fixation point is relocated to the 3D position by computing the whole-body joint positions with inverse kinematics.

After ending the tasks, the robot interacts with participants in the following social behavior: 1)Makes eye contact, speaks "*The experiment is finished. It was a great pleasure working with you!* (in Italian)" and makes a smile. All the behaviors in the "post-interaction" phase are designed to show social behavior. In particular, making eye contact is a typical social behavior between humans; the phrases that mention the pleasure of interaction show knowledge about social interactions and emotional feelings triggered by social interaction. Finally, the smile is a social-communicative behavior.

3.2.6.2 The nonsocial condition

Before starting the tasks, the robot cued the participants to begin the tasks by speaking "*Hello, I am going to start the experiment now* (in Italian)". All sociability is removed from the sentence, and it is designed more as a computer command without the social communicative characteristics.

After starting the tasks, the robot transitions among the four states shown in Fig. 3.3. In S_0, the robot turns its body (joint position control) to the monitor for 12 seconds, then turns to the participant for 6 seconds, and keeps cycling between these joint positions with repetitive motions (a_0). The behavior is designed to show a similar amount of movement for the social behavior but without a specific social meaning. In S_1, S_2 and S_3, the advice is given by the speech, "*Press F1(F2, F3, F4, F5 or F6),*" "*You pressed the wrong key,*" and "*Pay attention to the tracking activity*" in Italian respectively, in addition to the same motion in a_0 (a_1, a_2 , a_3).

After ending the tasks, the robot informed the participants that the tasks were finished, speaking "*I have finished the experiment* (in Italian)".

3.2.7 Questionnaires

I adopted the following questionnaires to analyze participants' internal state towards robots and tasks. In particular, the interaction with the robot has to be carefully assessed concerning the a priori attitude towards the robotic partner since the participant could address the robot with a positive or negative attitude during the first interaction.

- NASA-TLX (Post): To assess participants' subjective evaluation of cognitive workload towards the tasks, I adopted the NASA Task Load Index [72]. Here, in order to clearly distinguish between the subjective workload for the tasks assessed by the questionnaire and the unconscious workload by the electrodermal activity (EDA) (see section 3.2.8), I define the former as "cognitive workload" (only to the tasks) and the latter as "mental workload" (in the whole experiment including the tasks and stimulation from the robots(3.2.6)).
- Robot anxiety scale (RAS) [66, 67] (Pre and Post): I included the RAS in the pre and post-questionnaires, assuming that some participants initially have anxiety towards the robots and that the degree of anxiety may change before and after the experiment.

3.2.8 Integrated skin conductance response

In order to measure the mental workload of the participants during the task, I measure the electrodermal activity (EDA) also known as the GSR, which is regarded as a measure of activity by the sympathetic nervous system. EDA refers to changes in the electrical properties of the skin in response to sweat secretion. By applying a low constant voltage to the skin, changes in skin conductance (SC) can be measured noninvasively [73]. The time series of SC can be characterized by slow-changing tonic activity (i.e., skin conductance level; SCL) and rapid-changing phasic activity (i.e., skin conductance response; SCR). A series of SCRs is usually a superposition, as the subsequent SCRs occur on the decreasing trajectory of their preceding SCRs. Therefore, the scoring method using SCRs can be complicated when they are closely overlapping. Since the study involves continual task events and robot interactions, thereby generating overlaps of SCRs, I measure the mental workload of the participants using the integrated skin conductance response (ISCR) [74, 75], which is considered to be a robust and accurate measure of continual stimuli. Assuming that subsequent SCRs are superposed additively, the shape of the SCR can be affected by traces of preceding phasic activity [76]. Standard peak detection would be expected to underestimate the amplitude of subsequent SCRs if the decay trajectory of preceding activity is not taken into account. As such, standard SCRs can be used to assess only a response to a single event with sufficient convergence time, but when assessing tasks including continual events, as in the study, SCRs can be buried in the stimuli of preceding events. Hence, Benedek proposed ISCR, which is the integral value of the phasic driver [74, 75]. The ISCR captures the unbiased accumulative phasic activity by the entire response, taking into account the time dependency, rather than simply considering the peak of the response. As such, it is considered to be an appropriate measure of the overall affective volume within a given reaction period.

Therefore, the ISCR is more suitable than the standard SCR for measuring the mental workload in the study. The ISCR is represented by the following equation:

$$ISCR = \int_{t_1}^{t_2} Driver_{phasic} dt, \tag{3.1}$$

where t_1 and t_2 are the start and end times of the measurement, respectively. Also, $Driver_{phasic}$ is given by the following equation:

$$SC = (SC_{tonic} + SC_{phasic}) = (Driver_{tonic} + Driver_{phasic}) * IRF. \tag{3.2}$$

The IRF (impulse response function) is expressed as a Bateman function:

$$IRF = b(t) = e^{\frac{-t}{\tau_1}} - e^{\frac{-t}{\tau_2}}, \tag{3.3}$$

where the optimal values of the time constants τ_1 and τ_2 are calculated using the procedure described in the paper [75].

For the calculation of $Driver_{phasic}$ and ISCR, I used Ledapy 1.2.1 by Filetti [77], which is a Python reimplementation of the MATLAB library, Ledalab by Benedek *et al.* [78]. In order to assess the mental workload caused by the influence of each event of the task, ISCRs every 20 seconds in the 5 minutes period of the task are analyzed. As an EDA sensor, I used a Shimmer3 GSR+ module. The device has been proven as a reliable and accurate wearable sensor platform for recording biological signals [79, 80]. In my experiment, its electrodes are attached to the participants' index and middle fingers on their left hands.

3.2.9 Oral debriefing

The interviews were consistently performed after the end of the task and the following questions were asked: *Do you think that the task was difficult for you?*, *What do you think was the purpose of the robot's behavior?* , *Did you notice any robot movement?*, *Do you think that the robot's behavior helped you during your task?* The interviews were recorded with the use of a microphone and saved in the experiment analysis for further analysis of the single participant's feedback on the collaborative task.

3.2.10 Procedure

The experimenters welcomed the participants in a room that was previously prepared to be comfortable and dissimilar from typical laboratories. I also limited the distractions in the room that could affect the participant's performance by moving the experimenter control area behind the participants. The presence of the robot was initially resting in its home position, and from the moment the participant entered the room, I applied the following experiment protocol:

1. Participants were introduced to the pre-questionnaires and answered the pre-questionnaires in the presence of the inanimate humanoid robot, iCub.
2. Before starting the experiment, the experimenters asked participants to wear an EDA sensor on their left hand and explained how to operate the MATB-YARP. They were asked to operate the joystick with their left hand and the keyboard with their right hand.
3. Pre-interaction with the robot was performed before the MATB-YARP started. The robot's behaviors varied depending on the conditions.
4. The robot indicated the start of the MATB-YARP and the exercise started with events occurring in the time series.
5. After 5 minutes, the tasks stopped, the robot indicated the end of the MATB-YARP and post-interaction with the robot were performed after the tasks. The robot's behavior varied depending on the conditions.
6. Participants answered post-questionnaires after the experiment.
7. Experimenters proposed an oral debriefing and interviewed participants at the end of the experiment.

I designed the experiment protocol in steps to limit the interaction between participants and the experimenters. Instead, I based the entire experience on the interaction between the humanoid robot and the participant. The debriefing interview constitutes a meaningful investigation of participants' opinions on the experiment. The debriefing occurs after the end of the experiment and does not impact the data acquisition. It is also essential to record first-hand participants' feelings about the interaction.

3.2.11 Analysis

I recorded data from n_1 = 15 participants (5 female, 10 male) of the social condition data and n_2 = 13 participants (5 female, 8 male) of the nonsocial condition data were considered for the analysis. In the current study, two of the nonsocial trials were discarded because the robot was not working properly. For the evaluation of the experiments and my corresponding hypotheses, I assessed the following behavioral measures in the main tasks:

- The system monitoring task: *Reaction time from each event occurred.*

- The communications task: *Time from each event occurred to the completion of the radio frequency adjustment.*
- The tracking task: *Target distance to the center.*

3.2.11.1 Analysis for task performance and ISCR

The task performance of MATB and ISCR values were analyzed using the Aligned Rank Transform ANOVA (ART-ANOVA) [81] to evaluate the effects of time transitions and repeated trials and the effects of social and nonsocial condition differences. In addition, the Aligned Rank Transform Comparison (ART-C) [82] was performed as a post-hoc pairwise comparison for each event and each condition.

3.2.11.2 Analysis for questionnaire

For statistical analysis, I applied the Mann-Whitney U test [83] to the questionnaires. I used the SciPy version 1.5.4 for the U test. U values of the first and second groups are calculated as follows respectively:

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1, \tag{3.4}$$

$$U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_2, \tag{3.5}$$

where n_1 and n_2 mean the number of each group and R_1 and R_2 are the sum of the ranks for the first and second groups, respectively. Further, I compute:

$$U_1 + U_2 = n_1 n_2. \tag{3.6}$$

I defined n_1 and n_2 as the number of participants in the social and nonsocial conditions, respectively. To evaluate the effects, I used the probability of superiority (PS) [84] as an effect size as follows:

$$PS_1 = \frac{U_1}{n_1 n_2}, \tag{3.7}$$

$$PS_2 = \frac{U_2}{n_1 n_2}. \tag{3.8}$$

where U_1 and PS_1 are used to describe the differences from the nonsocial condition to the social condition. PS_1 is expressed as a number from 0 to 1. A result smaller than 0.5 means that the social condition has relatively larger values than the nonsocial condition, and a number larger than 0.5 means the opposite.

3.3 Results

In this section, I summarize the results of the experiment based on the three hypotheses raised. As a result of the analysis, H1 and H2 were supported and H3 was rejected.

- H1 is supported.
  The presence of the social robot significantly affected human performance on a cognitive task. In particular, the presence of the social robot improved performance on the system monitoring task compared to the presence of the nonsocial robot.
- H2 is supported.
  The presence of the social robot reduced the degree of mental workload during the cognitive tasks compared to the presence of the nonsocial robot.
- H3 is rejected.
  The presence of the social robot did not reduce the degree of anxiety towards the robot compared to the presence of the nonsocial robot, but rather increased it.

The details are summarized in the subsections that follow.

3.3.1 Hypothesis 1

The first hypothesis addressed whether the presence of a social robot would significantly affect human performance on a cognitive task compared to the presence of a nonsocial robot. To evaluate the hypothesis, I analyzed three tasks separately: the communication task, the system monitoring task, and the tracking task. To evaluate the effects of the time elapsed or repetitive trials, and the effects of both conditions, respectively, I applied the ART-ANOVA. The results of the analyses by the ART-ANOVA for the system monitoring, communication, and tracking tasks are shown in Table. 3.3, Table. 3.3, and Table. 3.3, respectively.

As shown in Table 3.3, there was a significant difference in the system monitoring task depending on the condition of the robot. At the same time, there is also a significant difference in each repeated trial, which is thought to include the effect of learning as the repetitive trials progress. On the other hand, there was no significant difference in the interaction between the two.

Next, as shown in Table 3.3, there was a significant difference in the communications task depending on the condition of the robot. At the same time, there was a significant difference in each repetition trial, which may be due to the fact that the number of keystrokes differs for each event because the radio channel and its frequency to be changed are different for each event. On the other hand, there was no significant difference in the interaction between the two.

Third, as shown in Table 3.3 shows that there was no significant difference in the tracking task depending on the condition of the robot, but there was a significant difference in the comparison over time. This may be due to the effect of learning over time and the fact that the other two tasks' events occurring at the same time and each event is different. On the other hand, there was no significant difference in the interaction between the condition factor and the period factor.

In summary, it was confirmed that a significant difference in the influence of task performance appeared from the results of the communications task, where the participants did not receive direct advice, thus H1 was supported. Therefore, it was confirmed that the presence of the social robot affected the performance of the cognitive task.

In addition, I evaluated the performance for each event of the system monitoring task and the communications task and each period of the tracking task using the ART-C to check more details. The results of the performance per event of the system monitoring task and the communications task, and the results of the performance every 20 seconds of the tracking task are shown in Fig. 3.4, Fig. 3.5, and Fig. 3.6, respectively.

From the analysis, there was no significant difference on the same events under the different conditions in the system monitoring task (e.g., [Social, 5th event(F6)]-[Nonsocial, 5th event(F6)]. Also, there was no significant difference on the same events under the different conditions in the communications task (e.g.,[Social, 2nd event(COM1)]-[Nonsocial, 2nd event(COM1)]). Moreover, there was no significant difference on the same periods under the different conditions in the tracking task (e.g.,[Social, 120-140s]-[Nonsocial, 120-140s]).

From the comparisons in the study, regarding the overall performance, the nonsocial condition was better in the system monitoring task where there was direct advice, and the social condition was better in the communications task where there was no direct advice. However, no significant differences were found in the individual event assessment.

table

Table 3.1: ART-ANOVA for the system monitoring task performance.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001.)$

	F	Df	Df.res	Pr(>F)	
factor(Condition)	5.13967	1	24.863	0.0323400	*
factor(Event)	2.33171	12	313.030	0.0071749	**
factor(Condition):factor(Event)	0.83652	12	313.026	0.6126775	

ART-ANOVA for the communications task performance.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001.)$

h

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factor(Event)	2.33171	12	313.030	0.0071749	**
factor(Condition):factor(Event)	0.83652	12	313.026	0.6126775	

	F	Df	Df.res	Pr(>F)	
factor(Condition)	6.9266	1	24.411	0.01449741	*
factor(Event)	6.5355	4	98.843	0.00010419	***
factor(Condition):factor(Event)	0.9172	4	98.960	0.45713014	

Table 3.3: ART-ANOVA for the tracking task performance.
($* = p < 0.05, ** = p < 0.01, *** = p < 0.001.$)

	F	Df	Df.res	Pr(>F)	
factor(Condition)	0.80189	1	24.959	0.37908	
factor(Period)	7.65928	14	365.003	3.4053e-14	***
factor(Condition):factor(Period)	1.01500	14	365.004	0.43728	

3.3.2 Hypothesis 2

The second hypothesis addressed the effect of the presence of a social robot on the mental workload compared to the presence of a nonsocial robot. To evaluate the hypothesis, I analyzed the ISCRs every 20 seconds in the 5 minutes period of the tasks and the NASA-TLX questionnaire. In order to assess the effects of the ISCRs over time and across the social and the nonsocial conditions, I applied the ART-ANOVA. As shown in Table. 3.4, I found that the ISCR was significantly different between the conditions of the robot, but there was no significant difference in the periods comparison. On the other hand, a significant difference in the interaction between the condition factor and the period factor was confirmed. Therefore, I conducted the ART-C for the ISCR to evaluate more details. The results of the ISCRs per period are shown in Fig. 3.7. As a result, no significant difference was found in the main effects of each condition and each period in the ISCR. On the other hand, significant differences appeared in the interaction, and I picked up the results of the comparison of the interaction right after the beginning of the task (0-20s) and at other time periods in Table **??**. In comparison to the period (0-20s), significant differences appeared for (120-140s), (140-160s) and (220-240s).

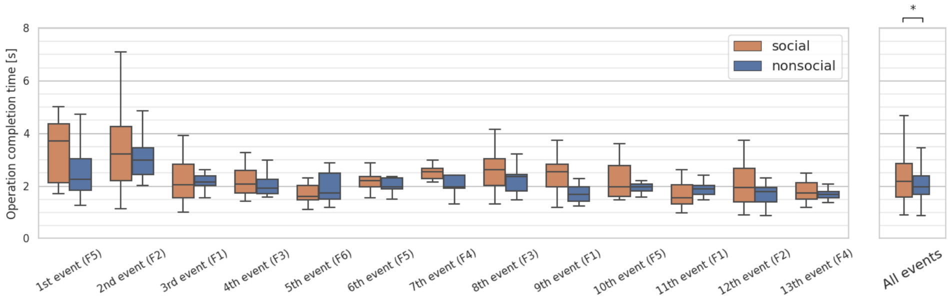

Figure 3.4: Evaluation of the reaction time on each event and at all events in the system monitoring task.
($* = p < 0.05, ** = p < 0.01, *** = p < 0.001.$)

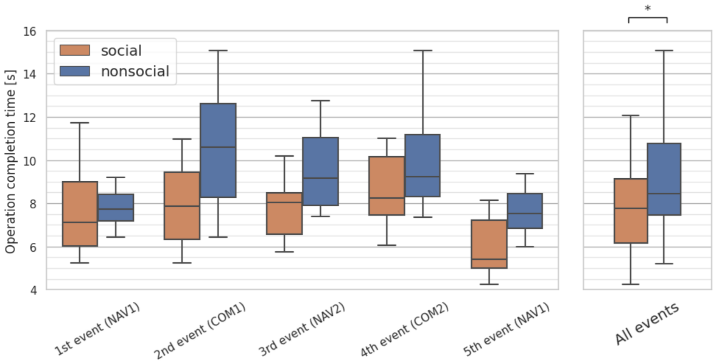

Figure 3.5: Evaluation of the operation completion time on each event and at all events in the communications task.
($* = p < 0.05, ** = p < 0.01, *** = p < 0.001.$)

Also, I analyzed the NASA-TLX questionnaire with the Mann-Whitney U test to see the subjective evaluation for the cognitive workload to the tasks by the participants. As shown in Table. 3.8, there was no significant difference between the two conditions.

From the results of the objective mental workload based on the ISCR, H2 was supported.

3.3.3 Hypothesis 3

The third hypothesis addressed the participants' anxiety towards the robot when interacting with it. To verify the hypothesis, the Mann-Whitney U test was applied to the RAS questionnaire, which was answered by the participants both before and after the tasks. As shown in Fig. 3.9, the changes of the S3 "anxiety for discourse with robots" ($p = 0.016, U_1 = 45, PS_1 = 0.23$, 95%CI= $[0, 4]$) and the total score ($p = 0.0017, U_1 = 29, PS_1 = 0.15$, 95%CI= $[2, 6]$) were

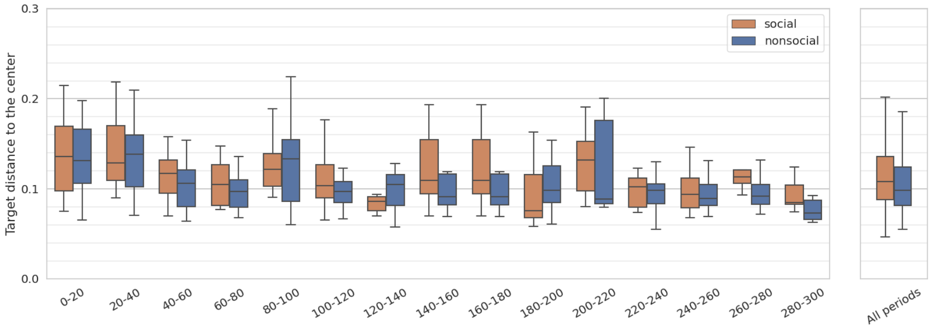

Figure 3.6: Evaluation of the target distance to the center on every 20 seconds period and at all periods in the tracking task.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001.)$

Table 3.4: ART-ANOVA for the ISCR values.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001.)$

	F	Df	Df.res	Pr(>F)	
factor(Condition)	14.5090	1	26	0.00076769	***
factor(Period)	1.0664	59	1534	0.34316420	
factor(Condition):factor(Period)	5.6057	59	1534	2.22e-16	***

significantly higher in the social condition. Therefore, the social robot rather induced more anxiety than the nonsocial robot, and H3 was rejected.

3.4 Discussion

Using data from 28 validated participants in the experiment, I analyzed the effects of two interaction styles of the humanoid robot on performance in multitasking, anxiety towards the robots, and mental workload. In the study, I set up an experiment in which the robots gave advice for the system monitoring task and the tracking task but no advice for the communications task during multitasking activities.

my results showed that participants in the social condition performed better in the communications task, which requires multiple key operations, and participants in the nonsocial condition performed better in the system monitoring task, which requires instantaneous responses.

Furthermore, analysis of NASA-TLX and ISCR revealed that participants in the social condition had a lower unconscious mental workload as measured by EDA, although there was no difference in the cognitive workload for the questionnaire-based subjective evaluation. This suggests

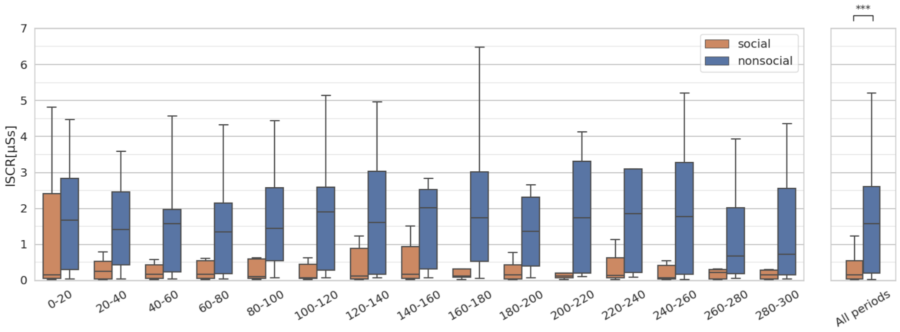

Figure 3.7: Evaluation of the integrated skin conductance responses (ISCR) on every 20 seconds period and at all periods.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001.)$

that the robot's expression of collaboration with the participants in the social condition made them feel at ease unconsciously, which improved their performance in the communications task; therefore, the influence of social facilitation appeared. In particular, Fig. 3.7 shows that even though the mental workload during 0-20s was high in both conditions, the value only in the social condition decreased remarkably after the period. This could be due to the fact that only the social robot was able to reduce the mental workload caused by stress in the unfamiliar experiment situation, through the social facilitation.

Moreover, the mental workload suddenly increased in the 120-140s and 140-160s periods only in the social condition while they are much smaller than the values of the nonsocial condition, which indicates the dominance of the interaction effect of the condition factor and the period factor. I believe that one of the reasons for this is the third event of the communications task occurred in the period. In fact, the most frequent keystrokes throughout the experiment were needed to raise the frequency of NAV2 from 120 to 180Hz for the third event. Nevertheless, in the social condition, the mental workload decreased again immediately after the period, which supports the assumption that the social facilitation from the social robot was working effectively. On the contrary, the nonsocial condition maintains a high mental workload throughout the experiment.

Although in Agrigoroaie *et al.*'s experiment [39], the robots spoke every four seconds and thus constantly stimulated people, in my experiment, I intentionally generated a period of silence, which could have led to a positive effect on social facilitation to the communications task performance. On the other hand, in the system monitoring task where direct advice was given, it was possible that the advice with social signals slowed down the instantaneous response speed, indicating that direct advice for a task that requires a quick response should be delivered mechanically in a concise manner.

However, the other indicators need to be carefully examined as well. I found that the failure rate of the communication task was higher in the social condition (7/75) than in the nonsocial

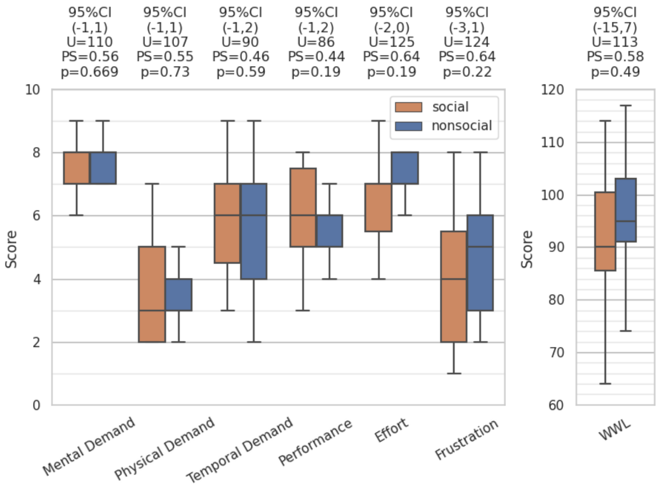

Figure 3.8: Evaluation of the NASA-TLX questionnaire. Each pair of box plots is evaluated with a 95% confidence interval (95% CI) and the p-values of the results are reported.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001.)$

condition (2/65). I consider that this is because the social robot allowed people to relax by the social facilitation and to intuitively manipulate their decisions in a short time, whereas the nonsocial robot made people analytic and allowed them to carefully manipulate their decisions. Therefore, it implies that mistakes can increase as operations become faster under the influence of the social presence of the robot. In order to maximize the team performance, some additional support system for such mistakes may be necessary, as well as the ability to positively express collaboration to humans to decrease their mental workload.

In addition, for the two indices, NASA-TLX and ISCR, a significant difference appeared only in ISCR. The results are similar to a previous study by Chao *et al.* in which only the EDA measurements showed a significant difference, but the NASA-TLX questionnaire ratings did not [85]. This implied that the subjective assessment by the NASA-TLX questionnaire and the objective assessment by the EDA are not necessarily assessing the equivalent components. Therefore, my results can be interpreted that the subjective evaluation of cognitive workload for the tasks was not significantly different in both conditions, but it emerged that the social facilitation by the social robot reduced the objective and unconscious mental workload throughout the entire social collaborative multitasking process.

In addition, it is suggested that in the social condition, the participants were more aware of the social presence of the robot due to the more anthropomorphic behaviors with social signals, which resulted in higher expectations as well as anxiety towards the robot during the interaction.

This result can be explained by the fact that most participants were unable to describe the behavior of the nonsocial robot in the debriefing after the task, even though the behavior of the

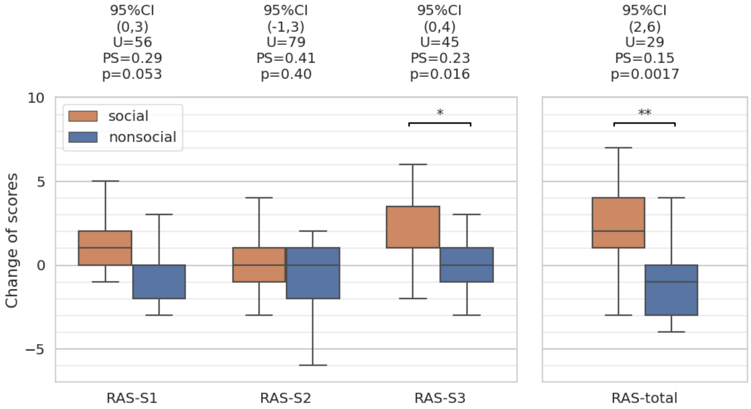

Figure 3.9: Evaluation of the changes in the robot anxiety scale (RAS) calculated from the pre- and post-questionnaires. Each pair of boxplots is evaluated at a confidence interval $CI = 95\%$, and the resultant p-value is reported. The highest difference between the two experimental conditions concerns the RAS-S3 and the RAS-total.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001.)$

nonsocial robot was mechanically repeated in a task-independent manner. Without perceiving the robot's behavior and not generating expectations, it also does not generate anxiety towards the robot. On the other hand, the human-like pointing gestures of the social robot were detected and recognized by most of the participants, and they were able to explain the behaviors in the debriefing. Therefore, I can conclude the results that the social robot had no negative effects, at least in terms of mental workload during multitasking, although anxiety toward the robot was higher in the social condition. One of the limitations of the study is that all participants were collected from employees in IIT, so the participants are more familiar with robots than the general public, although not all the participants are involved in robotics research. Therefore, it can be said that in both the social and the nonsocial conditions, the participants were relatively favorable toward robots as a prerequisite and were less likely to feel anxious or stressed when they were by the robots. Therefore, if all the participants are unfamiliar with the robot and are not friendly to it, the effect of social facilitation from the social robot may be limited. In addition, since the speeches in the experiment were given in Italian, I only included the participants who could speak Italian fluently. Since the language, as well as the recognized gestures, are different in other cultures, more extensive research is needed. Furthermore, since my experiment was conducted with a relatively small number of 30 participants (28 validated data), it may have been impossible to find some significant differences in the ART-C assessment due to statistical power issues in the pairwise comparisons. However, the ART-ANOVA detected the effects on the overall task performance and the mental workload, which were the main focus of the study. Thus, the main objective of the study was achieved.

3.5 Conclusion

This study presented the importance of social facilitation effects based on social presence as one direction for the design of robots that collaborate to engage in cognitive multitasking. Therefore, robot agents in supporting car and aircraft operation tasks also need to use social signals to show their social presence and to provide social facilitation effects. However, because it is not feasible to place a full-body humanoid robot in a car due to space constraints, some refinement is required. I describe the details in chapter 5. In addition, the study suggested the need to change the robot's behavior flexibly according to the task and situation. In particular, non-social mechanical behaviors are better for simple reactive tasks, and social behaviors are better for cognitively demanding tasks that require short-term memory. Since the study's results are impressive, though complex, it is essential to continue to investigate the impacts of HRI in multitasking scenarios under various conditions for a comprehensive analysis.

It is particularly important to investigate the impact of different social behaviors on cognitive tasks, as there are many different characteristics of social behaviors that people engage in. One of the perspectives is to focus on differences in vitality forms [44, 45, 46], and further experiments will be conducted in chapter 4.

Condition-pairwise	Period-pairwise	estimate	t.ratio	p.value	
social - nonsocial	(0-20) - (20-40)	-25.33	-0.926	0.355	
social - nonsocial	(0-20) - (40-60)	42.04	1.537	0.125	
social - nonsocial	(0-20) - (60-80)	0.1487	0.005436	0.996	
social - nonsocial	(0-20) - (80-100)	-10.76	-0.3933	0.694	
social - nonsocial	(0-20) - (100-120)	5.867	0.2144	0.830	
social - nonsocial	(0-20) - (120-140)	-121.9	-4.458	1.11E-05	***
social - nonsocial	(0-20) - (140-160)	-116.6	-4.262	2.59E-05	***
social - nonsocial	(0-20) - (160-180)	-21.70	-0.7935	0.428	
social - nonsocial	(0-20) - (180-200)	7.297	0.2667	0.790	
social - nonsocial	(0-20) - (200-220)	-23.85	-0.8718	0.383	
social - nonsocial	(0-20) - (220-240)	-55.05	-2.012	0.0449	*
social - nonsocial	(0-20) - (240-260)	-12.89	-0.4712	0.638	
social - nonsocial	(0-20) - (260-280)	28.34	1.036	0.301	
social - nonsocial	(0-20) - (280-300)	28.96	1.059	0.290	

Table 3.5: Tests of differences for the ISCR values using ART-C. I picked up the results of the comparisons between “0-20s” and the other time periods to compare the ISCR value right after the start of the experiment to the others. In all comparisons, SE (standard error) = 27.35, df (degree of freedom) = 364.
($* = p < 0.05, ** = p < 0.01, *** = p < 0.001.$)

Condition-pairwise	Period-pairwise	estimate	t.ratio	p.value	
social - nonsocial	(0-20) - (20-40)	-25.33	-0.926	0.355	
social - nonsocial	(0-20) - (40-60)	42.04	1.537	0.125	
social - nonsocial	(0-20) - (60-80)	0.1487	0.005436	0.996	
social - nonsocial	(0-20) - (80-100)	-10.76	-0.3933	0.694	
social - nonsocial	(0-20) - (100-120)	5.867	0.2144	0.830	
social - nonsocial	(0-20) - (120-140)	-121.9	-4.458	1.11E-05	***
social - nonsocial	(0-20) - (140-160)	-116.6	-4.262	2.59E-05	***
social - nonsocial	(0-20) - (160-180)	-21.70	-0.7935	0.428	
social - nonsocial	(0-20) - (180-200)	7.297	0.2667	0.790	
social - nonsocial	(0-20) - (200-220)	-23.85	-0.8718	0.383	
social - nonsocial	(0-20) - (220-240)	-55.05	-2.012	0.0449	*
social - nonsocial	(0-20) - (240-260)	-12.89	-0.4712	0.638	
social - nonsocial	(0-20) - (260-280)	28.34	1.036	0.301	
social - nonsocial	(0-20) - (280-300)	28.96	1.059	0.290	

Chapter 4

Effects of vitality forms from social robots on cognitive multitasking

4.1 Introduction

In chapter 3, It has been shown that social robots have the potential to relax people and improve their performance on cognitive tasks. It has been shown that social robots have the potential to relax people and improve their performance on cognitive tasks. While this is an important study evaluating the impact of social robots on cognitive tasks, further studies need to be conducted in depth in order to make better use of social robots. One of these is the study of how the behaviors should be performed in terms of vitality forms [44, 45, 46].

4.1.1 Vitality forms in human-human interaction

Cooperation in social groups requires the ability to cope with and correctly interpret the actions of others and to predict others' behaviors appropriately. When interacting socially with others, it is indicated that we can usually understand their behavioral goals and intentions [86]. There is evidence that the basic mechanisms underlying such abilities are related to a group of neurons with mirror characteristics [87, 88, 89], i.e., neurons that discharge in both action observation and action execution.

In social interactions, people behave gently, neutrally, or rudely, etc., expressing positive or negative attitudes toward others [44, 45, 46]. These behaviors characterize human behavior and provide information relevant to the agent's emotional state. For example, observing the way a person greets another person can tell us immediately if the person is happy or not, or if the person is in a good mood. A gentle tone of voice can convey friendliness and approachability, while a rude tone of voice can convey anger or frustration.

These attitude of people is expressed as their behavior, which can be termed as “forms of vitality” or “vitality forms” by Daniel Stern [90]. According to Stern, vitality forms are expressed through a range of behaviors and movements, including bodily movements, facial expressions, vocalizations, and other nonverbal cues. Vitality forms have a dyadic role in interpersonal relationships and Vitality forms allow social beings to communicate their attitudes, and the perception of vitality forms allows the receiver to understand the attitudes of partners [44, 45, 46].

It is important to note that vitality forms are distinct from emotions. Basic emotions are brief events characterized by visceromotor responses and behavioral preparation [91]. In contrast, vital forms reflect the agent’s internal emotional state and are superficialized as the way of human behaviors [90].

The ability to perceive and express vitality is already present in infants during mother-infant interactions, proving that vitality has an important role in relating to and understanding others [92, 93, 94]. In addition, the perception of vitality forms is impaired in individuals with social and communication deficits, such as children on the autism spectrum [95].

Most importantly, recent findings have shown that gentle or rude vitality expressed in voice or gesture can subsequently influence the recipient’s motor responses, and have been linked to a group of neurons with mirror characteristics that discharge during both action observation and action execution [44, 45, 46]. Di Cesare *et al.* have examined the neural correlates of vitality processing, showing that the perception and representation of vitality forms activate the dorso-central insula [96]. In a subsequent study, the same authors found that the same insula was activated not only when participants observed or imagined hand movements with specific vitality forms, but also when they heard action verbs or imagined pronouncing them gently or rudely [97]. These findings indicate that the dorsal central insula is involved in encoding vitality representations, regardless of the visual, auditory, or other modality by which the vitality forms are transmitted.

4.1.2 Vitality forms from social robots

Although humans and monkeys translate observed behaviors into their own internal representations, it has been shown that groups of neurons with mirror properties fire even when they observe the behavior of social beings of a species different from them [98]. The study showed that mirror neurons in monkeys respond when they observe human movement. The study suggests that these neurons are also likely to be involved in the ability to understand the actions and intentions of others across species boundaries.

In addition, Gazzola *et al.* identified the motor cortex involved in the execution of hand actions by humans and found that this motor cortex is strongly activated when viewing either human or robot actions [99]. Also, Oberman *et al.* showed that mirror neurons fire during the observation of hand movements by a humanoid robotic hand [100]. These studies suggest that mirror neurons can fire when an object is perceived as a social being, even if that object is not real life. Furthermore, Di Cesare *et al.* argued that the same motor cortex fires when observing a humanoid robot (iCub) [42, 43] that produces actions of different vitality forms, given that differences in perceived vitality forms affect motor responses and the same motor cortex fires when observing a robot [101, 102]. Di Cesare *et al.* implemented the kinematic features of human actions of different Vitality forms into iCub actions and showed that the dorsal median insula involved in Vitality forms is also active when humans observe the robot's actions [101]. In particular, they demonstrated that the velocity profile and peak velocity are more crucial for representing vitality forms than the 2/3 power law.

4.1.3 The aim of this study

My previous study focused on the effect of being with a social being, known as the social facilitation effect [103, 104] (see chapter 3). In the study, I evaluated the effects of a social robot that manipulates social signals such as facial expressions, gestures, gaze, and tone of voice on people's cognitive multitasking using the humanoid robot iCub. The results showed that participants completed tasks requiring short-term memory faster, and they were more relaxed with a socially behaving iCub than with a mechanically behaving iCub. This study showed that social robots could positively influence human task performance and stress through social facilitation effects. As a next step, it is crucial to evaluate how different behavioral styles of social robots affect cognitive task performances.

Therefore same as my previous study, I utilize a MATB-YARP [103] as cognitive tasks and an iCub as a collaborative social robot for the tasks in order to evaluate the effects of different vitality forms on task performance, mental workload, and facial expressions.

4.2 The study design

This section describes the hypothesis and design based on relevant studies, as well as a description of the tasks assigned to participants.

4.2.1 Hypotheses

Based on the research on vitality forms and my previous study on human cognitive tasks with social robots, I hypothesize the following:

- Hypothesis 1 (H1).
  People respond faster to a simple reactive task when they are with a rudely behaving robot than with a robot with a gently behaving robot.
- Hypothesis 2 (H2).
  People complete a task that requires short-term memory in less time when they are with a gently behaving robot than with a rudely behaving robot.
- Hypothesis 3 (H3).
  People perform better on a tracking task when they are with a gently behaving robot than with a rudely behaving robot,
- Hypothesis 4 (H4).
  People have more positive facial expressions and are more relaxed when they are with a gently behaving robot than with a rudely behaving robot

4.2.2 Experimental setup

All experiments were performed with the humanoid robot, iCub [42, 43], whose design and control infrastructure allows it to reproduce human-like behaviors resulting from specific cognitive models of human-human interaction. The participants performed the MATB-YARP task (see Sec. 4.2.3) which is a task battery that replicates several types of cognitive tasks that humans face when piloting an aircraft. The participants interacted with the MATB-YARP task for 5 minutes. The humanoid robot iCub (see Sec. 4.2.5) played a simple role of advising the start and the end of the task with different vitality forms for each condition, including its arms, torso and head movements during the whole MATB-YARP task. Fig. 4.1 describes the experimental setup.

4.2.3 Cognitive tasks (The MATB-YARP)

This study aims to explore human task performance and emotional states based on facial expressions when performing demanding cognitive multitasking in the presence of two types of social robots with different communication styles depending on vitality forms. Therefore, I adopted the MATB-YARP (see chapter 2), which can communicate through YARP (Yet Another Robot Platform) [41], allowing a complete controllable synchronization between the humanoid robot iCub robot and the task events.

Like the MATB and MATB-II tasks, MATB-YARP consists of four tasks: the system monitoring task, the tracking task, the communications task, and the resource management task. Here, I adopted three tasks, the system monitoring task, the tracking task, and the communications task. In the study, events on the system monitoring task and the communications task occurred in the timing shown in Fig. 4.2.

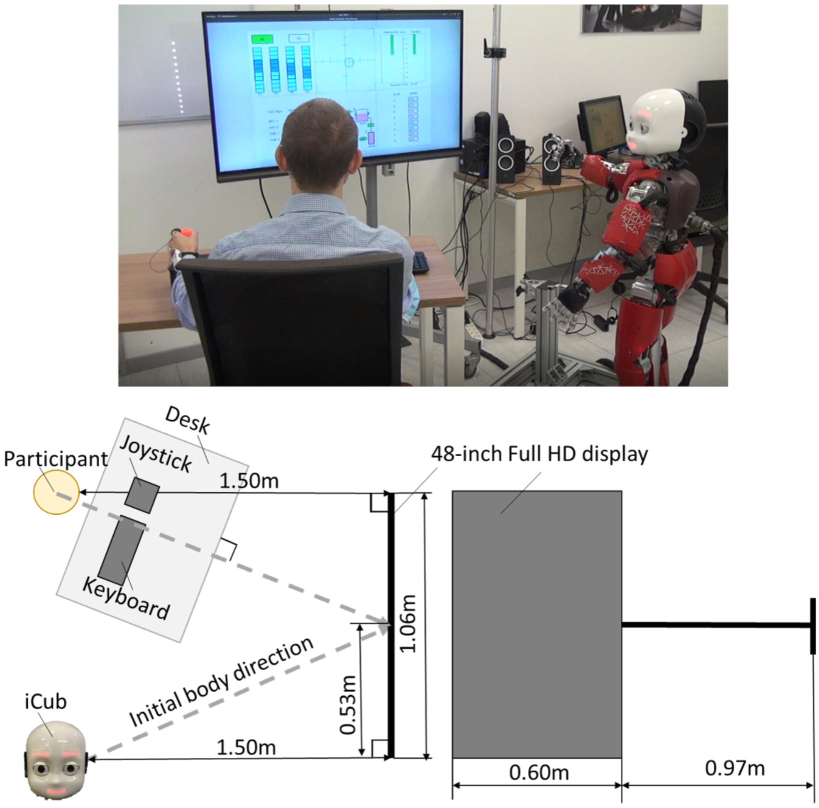

Figure 4.1: The experimental layout, showing the position of the participant, the iCub robot, as well as the recording devices.

In the tracking task, the target moves randomly in the $x(-1.0$ to $1.0)$ and $y(-1.0$ to $1.0)$ directions on each sample (30Hz) according to a Gaussian distribution (σ = 0.008, μ = 0 in this experiment). I designed the parameters to ensure that the target is controlled within the square while no other task events are occurring and that it is sometimes not possible to stay within the square while other task events are occurring. In the experiment, participants were encouraged to keep inside the small square ($-0.25 < x < 0.25, -0.25 < y < 0.25$) around the center. The tracking task is executed continuously from the beginning to the end of the 5-minute period in which MATB-YARP is performed. In the study, the average distances were measured every 20 seconds from the beginning of the task.

Of these multitasks, I asked participants to perform the following three tasks for 5 minutes that require responses from the participants, as same as the study in my previous study written in chapter 3 [103].

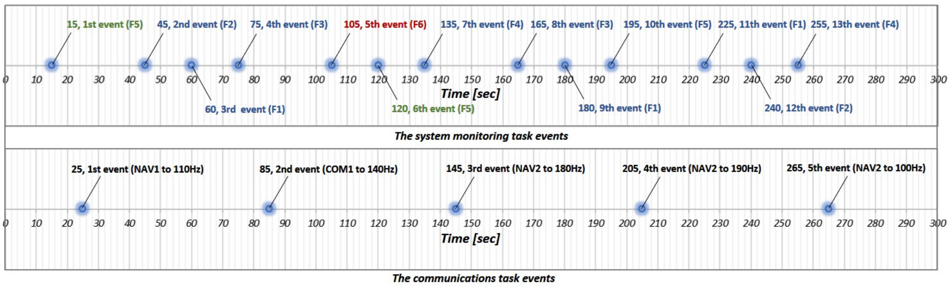

Figure 4.2: Outline of the MATB events for both the system monitoring task (first row) and the communications task (second row). The blue dots denote the timings and the expected inputs from the participants. The timings are the same as those of the study in chapter 3.

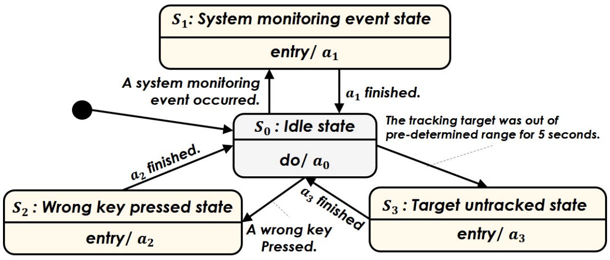

Figure 4.3: Finite state machine representing the flow of the interaction states with the iCub robot (see. section 4.2.5).

4.2.4 Participants

I recruited 29 native Italian speakers (18 to 54 years old, M=32.5, SD=153.6) from citizens in Genoa, Italy and randomly assigned 15 (9 female, 6 male) to the gentle condition and 14 (9 female, 5 male) to the rude condition to mitigate concerns about bias during recruitment. All participants volunteered to join the experiment and did not receive financial compensation. No one was familiar with the iCub robot, and all had completed at least undergraduate education. Each participant signed an informed consent form approved by the IIT ethical committee. The participants agreed to the camera and microphone recordings during the experiment and the data usage for scientific purposes. The research conformed to the ethical standards in the 1964 Declaration of Helsinki, which protects research participants. It was approved by the Liguria Region's local ethical committee in Italy (n. 222REG2015).

4.2.5 Stimuli (Interaction from robot)

In both gentle and rude conditions, the iCub interacts with the participants during the MATB-YARP exercise through physical movements and speech. All of the speech from the robot is Italian. Both conditions differ in vitality forms, i.e., the way they behave, which are described later in this section. The robot's behaviors in both conditions are based on the finite state machine shown in Figure 4.3. The control strategy of the robot transitions among four states. S_0 (idle state), S_1 (system monitoring event state), S_2 (Wrong key pressed state), and S_3 (Target untracked state). Transitions among states are triggered by events within MATB-YARP and by specific inputs from participants to MATB tasks. Among the three tasks in MATB-YARP, participants are supported by the robot's behavior and speech in the tracking and system monitoring tasks. On the other hand, the robot is designed to have no state transitions associated with the communication task in order to avoid conflict between the robot's speech and the air traffic control's guidance.

- S_0: Idle state
  The robot monitors the task on the display. While monitoring, the arms, neck, and eyes of the robot are continuously moving to the rhythm of human breathing.
- S_1: System monitoring event state
  The robot notifies the participant that a system monitoring event has been activated by pointing gestures to the display, gazing into the participant's face, and by speech. The phrase of the speech is: “ Premi F1 per piacere”. (“Press F1, please”. in English.)
- S_2: Wrong key pressed state
  The robot notifies the participant that s/he has made an incorrect keystroke by a pointing gesture to the display, gazing into the participant's face, and by speech. The phrase of the speech is: “Se ti posso aiutare hai premuto il tasto sbagliato”. (“ If I can help you, you have pressed the wrong key”. in English.)
- S_3: Target untracked state
  The robot notifies the participant that s/he is not following the tracking task by pointing gestures to the display, gazing into the participant's face, and by speech. The phrase of the speech is: “Scusami ancora, dovresti correggere la tua traiettoria. Ti prego, stai attento”. (“Sorry, you should correct your trajectory. Please, pay attention”. in English.)

The speech contents were based on a pre-recorded voice of an adult male actor. Using that voice as it was could cause participants to feel strange because of the gap between the iCub's slightly childish appearance and the adult male actor's original voice. Therefore, the pitch of the voice was slightly raised to match the iCub's appearance. The differences in the behaviors of the gentle and rude conditions are described hereinafter.

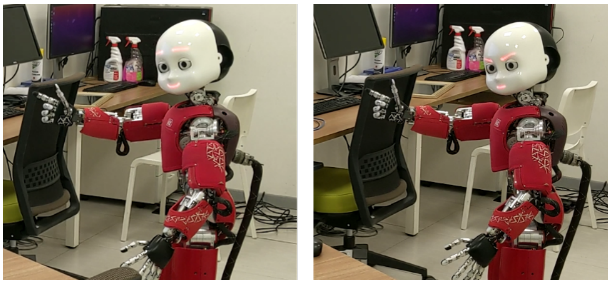

Figure 4.4: Robot behaviors and facial expressions in the gentle (the left image) and the rude (the right image) conditions.

4.2.5.1 The gentle condition

The gentle condition is characterized by the robot's calm, slow, positive behaviors. All of the movements are slow, and each movement, such as a pointing gesture, turning toward the participant, or re-looking at the monitor, is set to take 3 seconds, which is slower than in the Rude condition. Regarding facial expressions, when the robot gives advice, both inner and outer eyebrows are the same height, and the corners of the mouth are raised (see Fig. 4.4.). Regarding voice, plosive and accent are weak, and the robot speaks slowly.

4.2.5.2 The rude condition

The gentle condition is characterized by the robot's aggressive, fast, negative behaviors. All of the movements are fast, and each movement, such as a pointing gesture, turning toward the participant, or re-looking at the monitor, is set to take 1.25 seconds, which is faster than in the rude condition. Regarding facial expressions, when the robot gives advice, the outside of the eyebrows are lifted, and the corners of the mouth are turned up (see Fig. 4.4.). Regarding voice, plosive and accent are strong, and the robot speaks fast.

4.2.6 Integrated skin conductance response

In order to grasp the participant's mental workload during the task, I measure the mental workload of the participants using the integrated skin conductance response (ISCR) [74, 75], which is considered to be a robust and accurate measure of continual stimuli as in my previous study [103](see section 3 Although standard skin conductance responses (SCRs) can be used to assess responses to a single event with sufficient convergence time [76], ISCR is preferable for measuring mental workload for consecutive events as in my study, since each SCR may be buried in the preceding responses.

For the calculation of $Driver_{phasic}$ and ISCR, I used Ledapy 1.2.1 by Filetti [77], which is a Python reimplementation of the MATLAB library, Ledalab by Benedek *et al.* [78]. In order to assess the mental workload caused by the influence of each event of the task, ISCRs every 20 seconds in the 5 minutes period of the task are analyzed. As an EDA sensor, I used a Shimmer3 GSR+ module. The device has been proven as a reliable and accurate wearable sensor platform for recording biological signals [79, 80]. In the study, its electrodes are attached to the participants' index and middle fingers on their left hands.

4.2.7 Facial expressions

Facial expressions are measured in order to understand whether the robot's vitality forms during the task are propagated to the participants. The facial expressions of the participants are recorded with a USB camera placed on the monitor on which the MATB-YARP is projected at approximately 12-15 FPS at all times during the 5-minute tasks. For each frame of the recorded images, the participants' facial expressions are analyzed using the two-dimensional representation (arousal and valence) [105]. The higher the arousal, the less drowsy but energetic the participant is, and the higher the valence, the more positive the participant is. For the analysis of arousal and valence, I adopted FaceChannel deep neural network architecture [106]. In the FaceChannel network, each axis is represented by a range from -1 to 1.

4.2.8 Procedure

The experimenters welcomed the participants in a previously prepared room to be comfortable and dissimilar from typical laboratories. I also limited the distractions in the room that could affect the participant's performance by moving the experimenter control area behind the participants. The presence of robot was initially resting in its home position (expressionless, standing, facing forward), and from the moment the participant entered the room, I applied the following experimental protocol:

1. Participants were introduced to sitting on the chair in the experimental setup (see figure 4.1).
2. Before starting the experiment, the experimenters explained how to operate the MATB-YARP and asked participants to wear an EDA sensor on their left hand. They were asked to operate the joystick with their left hand and the keyboard with their right hand.
3. The robot indicated the start of the MATB-YARP with the speech, "Sei pronto ad iniziare? Ti devo comunicare che stiamo per iniziare l' esperimento, dai iniziamo l' esperimento, io sono qui per te". ("Are you ready to start? I have to inform you that the experiment is

starting, let' s start the experiment, I am here for you". in English.) Then, the exercise started with events occurring in the time series. The speed of the robot's behavior and its tone of voice vary depending on the conditions.

4. After 5 minutes, the tasks stopped, the robot indicated the end of the MATB-YARP with the speech, "Grazie, abbiamo finito con l' esperimento". (" Thank you, the experiment is terminated". in English.) The speed of the robot's behavior and its tone of voice vary depending on the conditions.

5. Experimenters tell the participant that the experiment is finished.

I designed the experiment protocol to limit the interaction between participants and the experimenters. Instead, I based the entire experience on the interaction between the humanoid robot and the participant.

4.2.9 Analyses

I recorded data from 15 participants (9 female, 6 male) of the gentle condition data, and 14 participants (9 female, 5 male) of the rude condition data were considered for the analysis. For the evaluation of the experiments, I assessed the following behavioral measures in the main tasks:

- The system monitoring task: *Reaction time from each event occurred.*
- The communications task: *Time from each event occurred to the completion of the radio frequency adjustment.*
- The tracking task: *Target distance to the center.*

In the communications task, events that took longer than 15 seconds to complete or were not responded to at all were treated as having a completion time of 15 seconds. In the experiment, 17 responses (5 responses in the gentle condition and 12 responses in the rude condition) are treated as such. Then, all 145 responses (75 responses in the gentle condition and 70 responses in the rude condition) were used for analysis.

In the system monitoring task, events that took longer than 5 seconds to react or were not responded to at all were treated as having a completion time of 5 seconds. In the experiment, 40 responses (22 responses in the gentle condition and 18 responses in the rude condition) are treated as such. Then, all 377 responses (195 responses in the gentle condition and 182 responses in the rude condition) were used for analysis.

In the tracking task, the target distance to the center is averaged every 20 seconds, and 15 data are obtained for each participant. Then, all 435 data from 29 participants (225 data from 15 participants in the gentle condition and 210 data from 14 participants in the rude condition) were used for analysis.

Also, each of the arousal and valence obtained from the facial expression data is averaged every 20 seconds, and 15 data are obtained for each participant. For the facial expression data, I excluded 1 participant from the gentle condition and 3 participants from the rude condition due to several pieces of data missing. Then, 375 data from 25 participants (210 data from 14 participants in the gentle condition and 165 data from 11 participants in the rude condition) were used for analysis.

In addition, the ISCR was calculated every 20 seconds, and 15 data were obtained in the 5-minute task. For the ISCR, in case the mean of 15 data from a participant exceeds 10 μSs, the participant is considered to have experienced excessive stress due to unfamiliarity with the experiment, and the data is excluded from the analysis. For the ISCR, in case the mean of the 15 data obtained from a participant is less than 0.2 μSs, the participant is considered to be extremely unlikely to experience skin sweating in general and the data is excluded from the analysis. In the experiment, 1 participant from the gentle condition and 3 participants from the rude condition were excluded. Then, 375 data from 25 participants (210 data from 14 participants in the gentle condition and 165 data from 11 participants in the rude condition) were used for analysis.

For statistical analysis, I applied the Mann-Whitney U test [83, 107] to the performances of the system monitoring task, the communications task, the tracking task, arousal, valance, and ISCR. I used the R version 4.1.2 for the Mann-Whitney U test.

4.3 Results

In this section, I summarize the experimental results based on the four hypotheses. The results of the analysis supported H2, H3, and H4, except for H1. Each of the analyzed data is summarized in the Tab. 4.3.4

4.3.1 Hypothesis 1

The first hypothesis addressed whether the presence of a rudely behaving robot would significantly affect human reactive performance on a cognitive task compared to the presence of a gently behaving robot. To evaluate the hypothesis, I analyzed the reaction time of the system monitoring task. In the system monitoring task, I obtained 13 data samples per participant and applied the Mann-Whitney U test to the responses to the system monitoring task events. As shown in Fig. 4.5, there was no significant difference in the reaction time of the system monitoring task ($p = 0.76, U = 1.7 \times 10^4$), and hypothesis 1 was not supported.

4.3.2 Hypothesis 2

The second hypothesis addressed whether the presence of a gently behaving robot would significantly affect human performance needed short-term memory on a cognitive task compared to the presence of a rudely behaving robot. To evaluate the hypothesis, I evaluated the operation completion time of the communication task. In the communications task, I obtained 5 data samples per participant and applied the Mann-Whitney U test to the responses to the communications task events. As shown in Fig. 4.6, the operation completion time in the gentle condition was significantly shorter than in the rude condition ($p = 0.040, U = 2.1 \times 10^3$). Therefore, hypothesis 2 was supported.

4.3.3 Hypothesis 3

The third hypothesis addressed whether the presence of a gently behaving robot would significantly affect human tracking performance, which required continuous focus on a cognitive task, compared to the presence of a rudely behaving robot. To evaluate the hypothesis, I evaluated the distance to the center of the target in the tracking task. In the tracking task, I calculated the mean distance to the center of the target every 20 seconds and obtained 15 data samples per participant for each, and applied the Mann-Whitney U test to them. As shown in Fig. 4.7, the distance in the gentle condition was significantly smaller than in the rude condition ($p = 6.9 \times 10^{-8}, U = 1.6 \times 10^4$). Therefore, hypothesis 3 was supported.

4.3.4 Hypothesis 4

The fourth hypothesis addressed whether the presence of a gently behaving robot would significantly affect human facial expressions and stress compared to the presence of a rudely behaving robot. To evaluate the hypothesis, I evaluated the arousal and valence from the facial expressions and the ISCR from the skin conductance. For the arousal and valence, I calculated the mean values every 20 seconds and obtained 15 data samples per participant for each, and applied the Mann-Whitney U test to them. As shown in Fig. 4.9, there was no statistically significant difference in arousal ($p = 0.64, U = 1.7 \times 10^4$). On the other hand, for valence, as shown in Fig. 4.10, the gentle condition was significantly higher than the rude condition ($p = 0.019, U = 1.9 \times 10^4$). For the ISCR, I calculated ISCRs every 20 seconds, and 15 data samples per participant were obtained and applied the Mann-Whitney U test to the data. As shown in Figure 4.8, the ISCR in the gentle condition was significantly smaller than in the rude condition ($p = 0.0014, U = 1.5 \times 10^4$). From the results of the valence and the ISCR, it is considered that the participants are relaxed with positive facial expressions. Therefore, hypothesis 4 was supported.

Items	Number of data		median		U	PS	95%CI		p	
	gentle	rude	gentle	rude			Lower	Upper		
SysMon[s]	195	182	2.11	2.11	1.7e+04	0.49	-0.33	0.26	0.76	
Comm[s]	75	70	6.88	7.95	2.1e+03	0.40	-3.67	-0.060	0.040	*
Tracking	225	210	0.10	0.12	1.6e+04	0.35	-0.056	-0.027	6.9e-08	****
Arousal	225	210	0.010	-0.0052	1.7e+04	0.49	-0.053	-0.038	0.64	
Valence	225	210	0.049	-0.023	1.5e+04	0.57	0.023	0.25	0.019	*
ISCR[μs]	210	165	0.79	1.31	1.5e+04	0.43	-0.998	-0.082	0.0014	**

Table 4.1: The statistical values obtained in this study are summarized. Here, "Sysmon", "Comm" and "Tracking" indicate the results of the system monitoring task, the communications task, and the tracking task, respectively. U are the statistical values in the Mann-Whitney U test. PS are the probabilities of superiority. p are the p-values.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = p < 0.0001.)$

4.4 Discussion

I analyzed the effects of two interaction styles of humanoid robots on multitasking performance, facial expressions, and mental workload using validated data from 29 participants in an experiment. In this study, I set up an experiment in which the robot gave advice for the system monitoring and tracking tasks, but not for the communication task, during a multitasking activity. My results showed that participants in the gentle condition performed better in the Communication task, which required short-term memory of voice instructions and performing multiple key presses, and in the Tracking task, which required continuous concentration. Furthermore, valence and ISCR analyses of facial expressions showed that participants' emotions were more positive and their unconscious mental workload was lower when they were with the gently moving robot. These findings suggest that under the gentle condition, the cooperative expressions of the robot unconsciously made the participants feel positive and relaxed, which improved their performance in the communications task, indicating the influence of the propagation of vitality forms.

On the other hand, in the system monitoring task, a simple reactive task, there was no statistical advantage between the two conditions, and the effect of the propagation of vitality forms was not confirmed. In the previous study by Di Cesare *et al.* [101], participants received an object after seeing an iCub offering it to them in a gentle or rude way. On the other hand, in my experiment, participants only operated the keys with their fingers, so I believe that the change in reactive movement speed was less apparent. I also found that the probability of completing the communication task within 5 seconds was lower in the gentle condition (5/75) than in the rude condition (12/70). This indicates that the gentle robot potentially relaxed the participants and was able to manipulate their decision-making reliably and in less time. Thus, the operation speed was increased and the probability of error decreased in the presence of the gentle robot, and the participants were able to relax with positive facial expressions, indicating that the presence

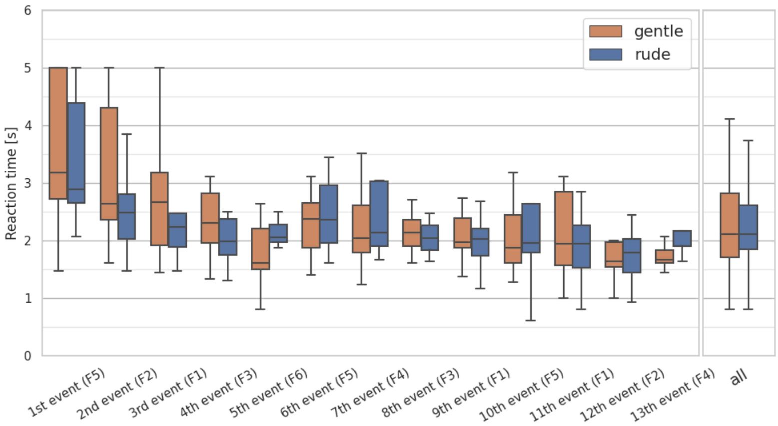

Figure 4.5: Evaluation of the reaction time on each event and at all events in the system monitoring task.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = p < 0.0001.)$

of a gentle robot has the potential to contribute to increasing team performance on cognitive multitasking.

Furthermore, this experiment showed coherent results for Arousal in facial expressions and ISCR in skin sweating. This result indicates that facial expression analysis using the deep learning model can replace skin perspiration in the measurement of stress. Although skin conductance data of some participants could not be included in the analysis due to the noise and extreme stress of the experiment, based on the results of this study, the simultaneous use of facial expression and skin conductance should improve the validity of experimental results of also for future studies.

Limitations of this study include the fact that the participants were Italian, whose facial expressions tended to be larger than those of other cultures. In particular, studies have shown that people from East Asian cultures, such as Japanese and Chinese, tend to express emotions in a more subdued and subtle way than Westerners. Therefore, if my experiment were conducted in such regions, it is possible that significant differences in facial expressions would be difficult to detect. Moreover, since this experiment was conducted with a relatively small number of 29 participants, it is possible that I could not find significant differences due to statistical power issues in the system monitoring task. One another possible reason for this may be that participants were focused on the task and were unable to observe the rude behaviors of the robot, and the effect of intonation differences alone may not have been sufficient to speed up human reactive behavior.

In addition, this study was not conducted using FMRI analysis in neuroscience to determine whether Vitality forms were propagated in mirror neurons. Future research could be conducted in terms of mirror neuron studies to determine whether vitality forms propagate during cognitive

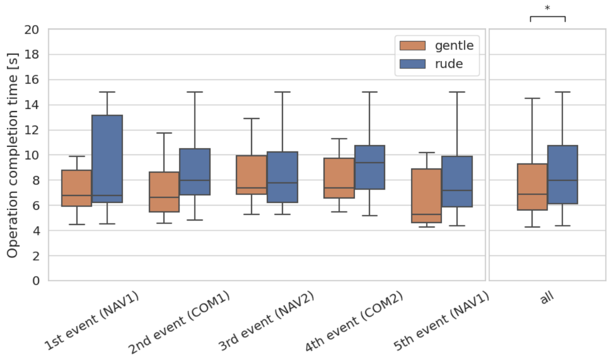

Figure 4.6: Evaluation of the operation completion time on each event and at all events in the communications task.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = p < 0.0001.)$

tasks.

4.5 Conclusion

This study underscores the critical role of vitality forms in the robot that collaborates in cognitive multitasking. Therefore, robot agents supporting tasks in car and aircraft operations must also adapt their behavioral speed and tone of voice to convey their vitality. However, it is s not practical to place a full-bodied humanoid robot inside a car due to space limitations, as discussed in chapter 3. The details are described in chapter 5. Also, this study contributes in two ways to the research of vitality forms which are gaining increasing attention in neuroscience. It is the first study that examines their effect on collaborative cognitive tasks with a social robot. Furthermore, this study indicates that vitality forms propagate not just from a single cognition to a single action but work in longer time scales as in our 5-minute collaborative tasks. This is important, especially for commercial applications with large numbers of users, where the long-term effects of human-robot interaction on real-world collaborative tasks should be cautiously considered in addition to short-term effects. This study may also provide a foothold towards exploring the long-term effects of vitality forms on real-world human-human interaction beyond controlled experiments. As such, this study is a crucial step not only for the research of vitality forms but also for social robot communication in general.

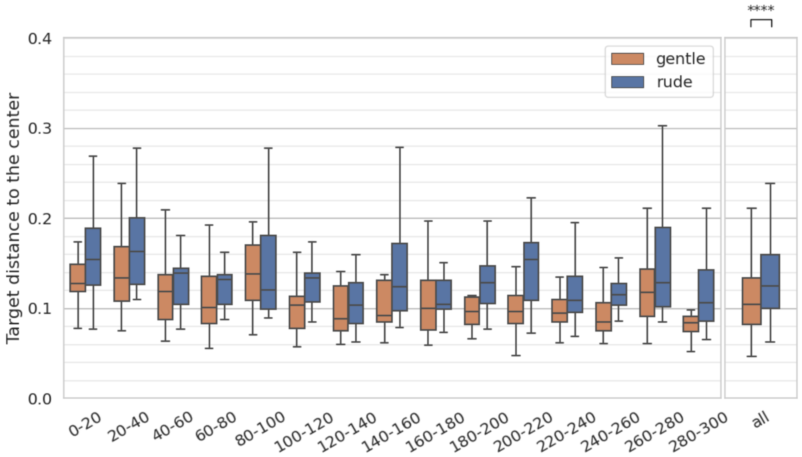

Figure 4.7: Evaluation of the target distance to the center on every 20 seconds period and at all periods in the tracking task.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = p < 0.0001.)$

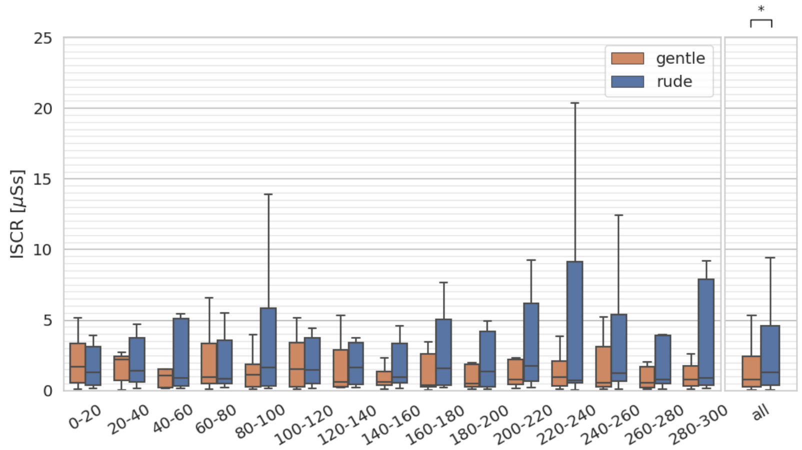

Figure 4.8: Evaluation of the integrated skin conductance responses (ISCR) on every 20 seconds period and at all periods.
$(* = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = p < 0.0001.)$

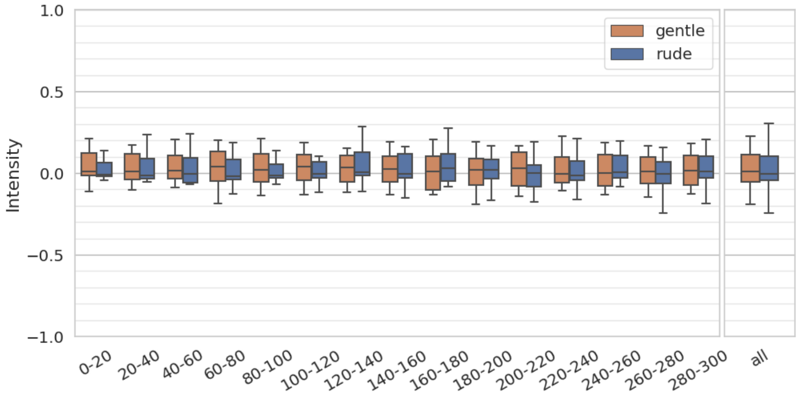

Figure 4.9: Evaluation of the arousal values on every 20 seconds period and at all periods. $(* = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = p < 0.0001.)$

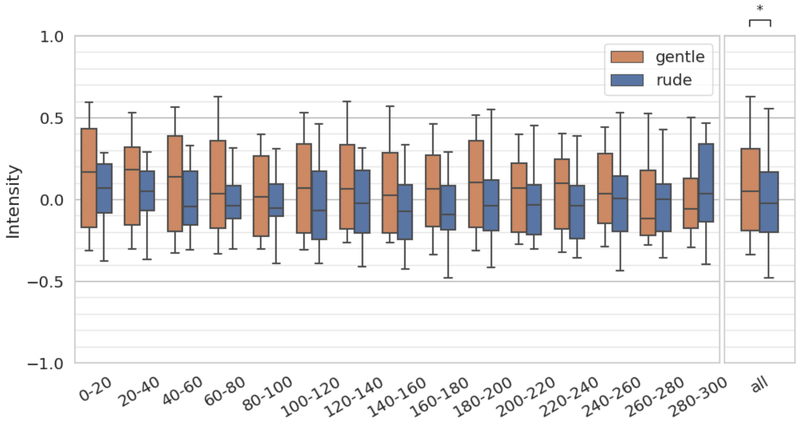

Figure 4.10: Evaluation of the valence values on every 20 seconds period and at all periods. $(* = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = p < 0.0001.)$

Chapter 5

Development of a car-mountable social robot head that can express vitality forms

5.1 Introduction

In chapter 3, I showed that social robots have the potential to relax people and improve their performance on cognitive tasks, and in chapter 4, I showed that social robots behaving in gentle vitality forms relax participants and make their facial expressions more positive, and also improve their performance on cognitively demanding tasks that require short-term memory. These studies are important for applying social robots to industrial fields that require cognitive tasks. While new findings revealed that social robots could be useful in industry, humanoid robots such as the iCub are too large to be implemented in a car or cockpit of an airplane. Hence, it is not easy to place a social humanoid robot as it is. Therefore, as one of the measures to solve the size limitation, I developed a novel social robot that utilizes the iCub robot head without a torso.

However, if the body is removed, the social behaviors using the arms and hands are lost, and the presence of the robot as a social being can be decreased. In a previous study, Younbo *et al.* compared the differences in social presence between social robots with and without a torso and found that social presence was lower without a torso [108]. In contrast, Heerink *et al.* showed that more social behaviors, such as nodding, the variable pitch of speech, and facial expressions, increased social presence when interacting with a robot [109]. Also, in a non-robot study, Tung *et al.* compared social presence using a static Emoticon and a dynamic Emoticon with continuously changing facial expressions and found that the dynamic emoticon had a higher social presence [110]. Based on these previous studies, improving the richness of facial expressions is important for robots collaborating on cognitive tasks even when the torso is eliminated. To address the problem of decreasing the variety of social behaviors and social presence due to removing the torso, it is necessary to complement them with other elements. As one of the elements in the head, I worked on improving the iCub's eyebrows in order to ensure the means of expression as a social robot since the conventional iCub can express limited eyebrow behaviors by discrete LED representations. Thus, the effects of social facilitation effects and vitality forms shown in chapters 3 and 4 can be ensured in the robot head. In addition, the discrete representation of the conventional LED eyebrows of the iCub has a problem of making it difficult for humans to recognize their facial expressions. Facial expression changes that differ from biological movements make it difficult to understand facial expressions [111]. It has been shown that (1) two frames at the beginning and end and (2) nine frames from the beginning to end are more difficult to recognize facial expressions than (3) a video with continuous and smooth changes in facial expressions [112]. Therefore, the novel eyebrows I develop aim to change their shape and speed according to the vitality forms, thereby simultaneously enhancing the robot's social presence.

5.1.1 Facial expression changes at different speeds

Human facial expressions are essential parts of non-verbal communication and play an important role in social interactions. A smile or an angry facial expression is a social signal that can be interpreted by the receiver as a positive or negative response from the sender. In facial expressions, the role of the eyebrows in social interaction has been a long-overlooked significant feature in human faces [113, 114, 115]. For example, it is shown that the absence of eyebrows had a more negative impact on face recognition than the absence of eyes [116]. The seminal work of Ekman [3] showed the diverse set of facial expressions of eyebrows including bending and frowning. Until now, several studies investigated the role of different face elements [115, 117] and their impact on critical aspects in human-robot interaction (HRI) such as trust [118] and acceptance of robots [119, 120].

Also, the importance of the speed of facial expression changes has gradually become apparent in the context of "subtle facial expressions" [112, 121, 122, 123, 124, 125]. Subtle facial expressions are defined as "emotional expressions that involve relatively low-intensity and/or few appearance changes in the face" [126]. Although it is difficult to recognize subtle changes in facial expressions statically, it has been found that people can distinguish subtle happiness, sadness, and pain by capturing these changes dynamically [112, 121, 122]. Actually, people do not always make extreme facial expressions, but rather they continuously make relatively small changes in facial expressions due to subtle changes in their feelings. Furthermore, it is known that the rate of change in facial expressions varies with emotion. Sowden *et al.* tested the differences in facial expressions across emotions from both behavioral and cognitive perspectives [127]. According to the studies, they examined the speed of facial expression change in the emotions of happiness, anger, and sadness, and found that facial expression of happiness was the fastest and that of sadness was the slowest. Furthermore, in recognition of facial expressions, they found that faster facial expression changes were more likely to be perceived as happiness or anger, while slower changes were more likely to be perceived as sadness. In addition, Recio *et al.* showed that sadness is most easily recognized at slow speeds, while disgust is most easily recognized at high to medium speeds [128]. Thus, as with the vitality forms I dealt with in chapter 4, changes in the speed of behaviors are also focused on in facial expressions. Then, it can be seen as the difference between sadness and disgust as the difference between gentle and rude vitality forms in negative emotions expressed in a slow behavior, and in a fast behavior.

Based on these research results, the importance of more flexible control of eyebrows, including their speed, to express more human-like emotions in social robots has been recognized in recent years. By enabling robots to recognize and control facial expressions including different vitality forms, such as sadness and disgust, or contentment and happiness that human beings use in their daily lives, humans recognize robots more as social beings, their companions, and human-robot communication becomes more effective.

5.2 Related work

5.2.1 Three main approaches for robot head design

However, every humanoid robot platform has unique features and task requirements [129], which is why there are different approaches to eyebrow design, and controlling the speed of facial expressions to produce vitality forms and subtle facial expressions is not straightforward. For humanoid robot heads, there are three main approaches. The first one is to express the face with skin made of elastic material and to move the eyebrows, mouth, etc. from inside the skin [130, 131, 132].

The second one is to use the face itself as a display to change the appearance of the face or to use LEDs or projectors to illuminate the surface of the face from the inside [133, 42, 43, 134]. This is the approach used in the iCub [42, 43] which was utilized in this study, and in the Furhat [134, 135, 136] by Furhat Robotics. Both the Furhat and the iCub are social robots designed to interact with humans, with conversational capabilities through speech, eye contact, gaze, and facial expressions. The Furhat is a stationary robot with a human-like face that can be customized with projection to fit different use cases while iCub is a full-body humanoid robot that uses motors to control the physical hardware for the eyes and eyelids with the eyebrows and mouth represented by illuminated LEDs from the inside of the face. Therefore, although there are differences between the two in eye contact and joint gazing using the eyes and eyelids, the concept of eyebrow and mouth expression is similar. However, the Furhat projects its face with more complex lights illuminated from the inside, allowing for more flexible eyebrow and mouth expressions than the iCub.

The third one is to compose the eyebrows, mouth, etc., as separate parts on the skin, which is mostly made of rigid material, and to move them directly by actuators [137, 138]. While the first approach allows for complex facial expressions, it has the disadvantage of making it difficult to control the movement and wrinkles of its skin using internal actuators, which could fall into the uncanny valley [139] unless well designed. In the second approach, the face itself can be used as a display for a variety of expressions, but its three-dimensional shape cannot be changed from the predetermined shape, so there is a risk that people may be confused about the feeling of depth. The third approach, on the other hand, tends to have simpler expressions than the first approach but is relatively easy to control because it does not involve skin control while maintaining that sense of depth, different from the second approach.

While all research directions are important, I chose the third approach because the first approach has not yet fully understood how to manage the uncanny valley problem by controlling its skin, and the second approach can affect the sense of depth and may result in a "mechanical" feeling.

In creating hardware that can represent vitality forms with facial expressions, the developing mouth is more challenging, as it needs to adapt its movements not only to express emotions but also to speak. Therefore, this study focused on achieving eyebrows that can change shape and speed, which has been difficult to achieve with conventional eyebrows.

To achieve this goal, I adopted a wire-driven flexible mechanism to control the eyebrows, which has been developed mainly for surgical robots. This method is inspired by the mechanism of biological organisms and achieves high controllability and flexibility with a material that is only a few millimeters thick. In this study, I describe the specifications of my prototype, i.e. a biomimetic, wire-driven eyebrow design for the social robot "iCub" [42, 43], which has been included in numerous HRI scenarios. I also discuss the types of research that can be conducted using the novel design.

5.2.2 Eyebrows as additional parts on robots

There have been two approaches to designing an eyebrow as an additional part on the surface of the face. One is to use actuators mounted inside the face to raise, lower, or rotate an eyebrow made of a rigid material, such as NAO [137], Nexi [138], WAS-4 [140] or Flobi [141]. The other is to raise, lower, or twist the end of the brow made of elastic material by the SEER [142].

The former approach, being made of rigid bodies, has limited degrees of freedom and cannot replicate the complex shape changes of a human eyebrow. On the other hand, trying to raise its expressiveness increases the number of links, leading to the complexity of the structure [143]. The latter approach, on the other hand, allows for the generation of complex shapes since each actuator applies force to the entire eyebrow. However, there are still a few examples of eyebrow control using elastic materials, and sufficient dynamic analysis has not yet been conducted. At least with the method of twisting the elastic material in the SEER [142], it has been suggested that the elasticity and force applied determine the shape of the eyebrow, which makes it difficult to replicate the same eyebrow manipulation repeatedly.

5.2.3 Biomimetic wire-driven mechanism

A method that satisfies all the requirements of 1) being a few millimeters thick, equivalent to a human eyebrow, 2) being elastic, and 3) having high controllability is a wire-, cable-, or tendon-driven mechanical system used in surgical robots.

Matteo *et al.* [144] presented a robotic arm inspired by the octopus. Further, the wire-driven actuators, that is, an inextensible wire, are connected between the soft actuators and the designed components to provide precise position and force control. Moreover, this wire drive has adequate friction and very high tensile strength along its longitudinal axis to easily fit into the soft actuators or designed components. One such example is the successive use of wire-, cable-, or tendon-driven actuators in surgical robotics instruments [145]. The additive manufacturing industry has been able to provide softer, more durable, and resilient 3D printed materials thanks to the diversification of such materials. Soft robots are being 3D printed, with the use of diversified materials to provide, for example, flexibility, friction, variable stiffness, and so on, to overcome the limitations of traditional rigid body systems.

5.3 A novel 3D eyebrow design

On the basis of related works, I aim to develop continuous and dynamically manipulable eyebrows using a wire-driven mechanism to achieve a stronger presence as a social being, so-called, “social presence” [13, 146, 12] and express vitality forms.

5.3.1 Mechanical design

I adopt the biologically inspired manipulations, the so-called Continuum Bending-Type (CBT), that have the following properties: elementary control of soft actuators, elastic material, and simple structure, to provide flexibility and compliance [147].

This study focuses on improving the eyebrows of robots, which can be attached to the iCub’s face to mimic human eyebrow behaviors. Considering the size of the human eyebrow, I need to create a structure with a height of about 10 mm at most and a thickness of about 3 mm or less. Besides, since I use elastic materials, the shape, size, and stiffness of the material itself will affect the manipulation of the eyebrow.

The work presented here has the purpose of continuously changing the eyebrows’ behaviors, such as raising and lowering, like human eyebrows.

5.3.1.1 Mechanical aspect of the eyebrow structure

In this section, I emphasize the mechanical functioning of the designed eyebrow structure, which helps to understand the bending mechanism to mimic an eyebrow action on the iCub face cover. Fig. 5.1a describes the eyebrow structure in CAD, where L is the length of the structure, W is the width, and d is the distance between the `structure central axis` and the `wire central axis`. Here, two wires pass through the eyebrow structure internally to enable the bending mechanism. The eyebrow structure has been equally divided to the `grooves` (with a dimension of 3.5 mm) in the `longitudinal sides` to provide a constant stiffness across it to support smooth bending. The bending is a movement in the eyebrow's structure where one of the two longitudinal sides contracts in the `structure central axis`. Smaller contractions across these `grooves` provide the overall bending of the eyebrow structure. For instance, the functioning of the vertebrae in respect to bending. In the case of demonstration, I have used simple geometry to evaluate the curvature of the bending mechanism (see Fig. 5.1b).

An important perception in the eyebrow structure design is the symmetrical shape with respect to the middle neutral plane, that is, the plane passing through the `structure central axis`. Fig. 5.1c shows the structure along with the `grooves` shrink when the wire passing through the `wire central axis` is displaced (the wire is pulled) by Δl. This action alters the wire length on its corresponding side to $L - \Delta l$. Concurrently, the alternative longitudinal side where the structure stretches the wire length in the same amounts to have $L + \Delta l$. However, the central length in the `structure central axis` remains unchanged. Whilst contracting, the successive side curves form an arc of circumference. Let' s name the radius of this arc to be R and let the β be the angle of curvature.

$$\frac{R}{L} = \frac{R - 2d}{L - \Delta l} \tag{5.1}$$

Using simple geometric calculations, it is possible to evaluate the circumference radius,

$$R = \frac{L.2d}{\Delta l} \tag{5.2}$$

from [144]. Whilst the angle of curvature β in radians is calculated from L/R. Further, the relationship between the angle generated at the motor α and Δl at the pulley is given by,

$$\alpha = \frac{2.\Delta l}{P} \tag{5.3}$$

where P is the diameter of the pulley.

5.3.1.2 Assembly of the eyebrow structure

The arrangement proposed for the robot's eyebrow offers a significant advantage over the bending mechanism. The major design constraint is that the eyebrow structure must remain symmetric

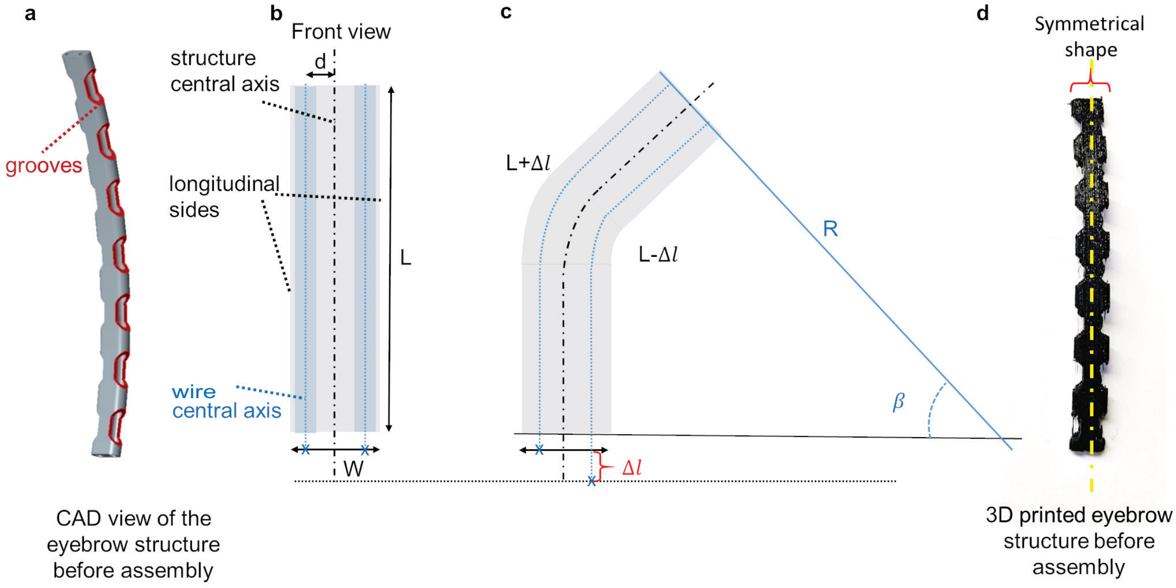

Figure 5.1: **a.** Geometry behind the eyebrow structure, **b.** Illustrates the eyebrow bending mechanism when the wire is displaced with Δl, **c.** The CAD view of the eyebrow structure without any curves, and **d.** The 3D-printed eyebrow structure was used in this experiment.

on the bending plane. Therefore, this structure was designed with the symmetrically corrugated CBT as shown in Fig. 5.1. Moreover, the eyebrow structure has been designed to have constant stiffness across itself; such could provide uniform force distribution for the need of actuation.

To assemble this eyebrow for actuation, both ends of the corrugated structure are designed to have two openings on either side matching the outer diameter of the wire to be contained (see Fig. 5.2). The wire is inserted into the eyebrow structure in the `Path for wire` through these openings, and one end of the wire is attached to the `Rigid cap` to clamp the wire on one side of the eyebrow. The other end of the eyebrow is connected to the `Motor` (Faulhaber 1224N-SR motor in addition to a 10/1K 256:1 planetary gearbox and HEM3-256W encoder) through a small `Pulley`. Here, the pulley is custom-designed to clamp the other end of the wire to the actuator. Finally, the assembly is mounted onto the `Mechanical support` to fix them on the iCub face cover. Then, this proposed structure creates a closed connection with the actuator to support the translational motion. The appropriate use of the structure provides a variety of geometric patterns with the effect of which the bending motion is characterized. Finally, two eyebrows of this structure are attached above the left and right eyes of the iCub head, respectively, as shown in Fig. 5.3.

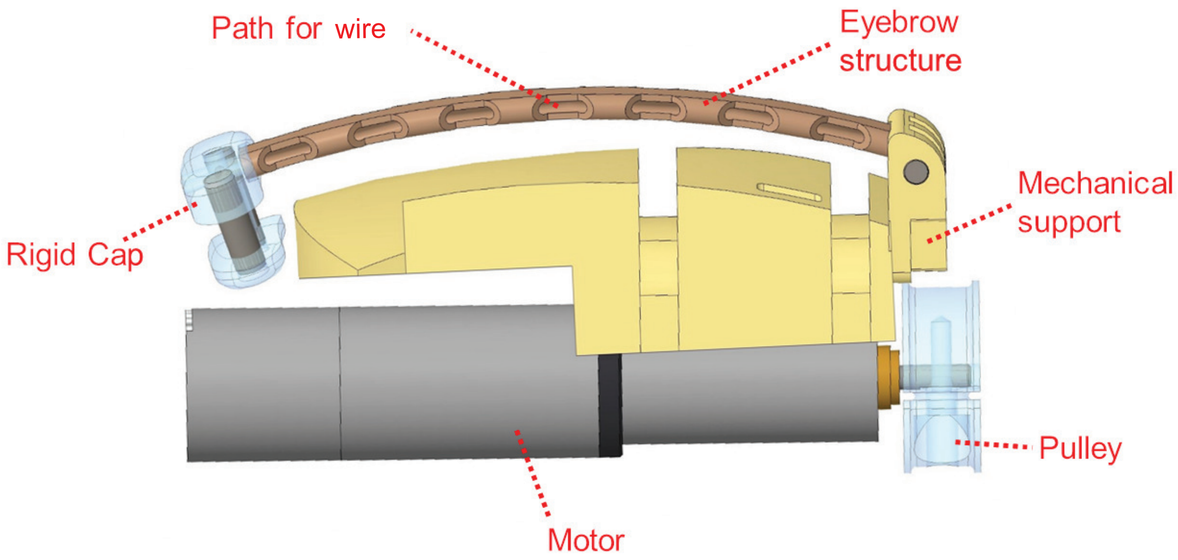

Figure 5.2: CAD view of the eyebrow assembly

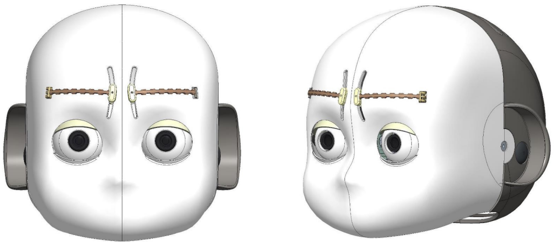

Figure 5.3: The iCub head design with the novel eyebrows

5.3.2 Electronics design

Thanks to Metta *et al.* for developing a motor control board for the DC motors. The 4-channel brushed DC motor board was re-programmed for the precise positioning of the motors [43].

5.4 Evaluation

5.4.1 Evaluation of the eyebrow actuation

In this section, I discuss the resulting eyebrow structure designed with a constant stiffness across the entire eyebrow. Before experimentation, I characterized the bending limits in the eyebrow structure based on the above relations (described in Section 5.3.1.1). The physical parameters for defining bending limits are P = 14 mm, d = 1.2 mm, thickness = 3 mm W = 4 mm and L = 52 mm are used in the Eqn. 5.2. These parameters give the maximum possible limits in terms of wire displacements Δl in the eyebrow structure, such that every small change in Δl will give a new position in the eyebrow structure placed on the iCub face cover to show emotion. The Δl will be displaced from 0 to 10 mm to slide or bend the eyebrow structure on the face cover for $46°$ as shown in Fig. 5.4a. This bending mechanism completely relies on motor rotation, that is, the motor rotation angle α alters or changes the wire displacement correspondingly. The rotation angle is calculated using Eqn. 5.3, where for the given Δl the angle generated is 80 °, that is, $\pm 40°$ on either side. Fig. 5.4b shows the rotation angle used in the eyebrow structure to move up and down or towards and backward both with the iCub face cover and without them for every given emotion. Fig. 5.5a shows the theoretical evaluation for bending characterizing motor angle α, angle of curvature β along with the wire displacement Δl. The eyebrow structure is now characterized for bending, the linear translation allows the experimenter to position the eyebrow structure to display any emotions.

5.4.2 Practical validation of eyebrow actuation

Now, the bending mechanism is characterized, and the maximal limits are known, I need to validate the eyebrow motions in correspondence with α and β practically. For this validation, I have programmed the controller (see 5.3.2), which varies the DC motor to various angles, and their corresponding values are noted. Then, the new position at the eyebrow structure in the iCub's face cover is also recorded. Fig. 5.5b shows the plot of the motor angle vs ground truth angle of curvature sampled during a set of random trajectories. The statistical analysis reveals the R^2 value between α and β for the plot was found to be 99.61%.

This bending mechanism replicates the muscle actions of *pars medialis*, that is, I transferred the rotations from the motor to vary α to provide the requested emotions. In this experiment, the 3D print material used for the eyebrow structure had the following properties, elastic modulus 2410 N/mm^2, Poisson' s ratio 0.3897, and shear factor 862.2 N/mm^2 to provide better flexibility [148].

However, with the advancements in 3D printing technology, it is reasonable to think of different shapes having variable stiffness "H", where the rigid segments can be introduced inside the flexible component or asymmetrical structures could be incorporated to bring many new perspectives into this area, especially bringing biologically inspired motions for realizing emotions. In the case of introducing the stiffness parameter, Eqn. 5.2 will be varied as such by introducing a variable stiffness parameter, “H”,

$$R = \frac{(L - H).2d}{\Delta l} \tag{5.4}$$

from [144].

5.4.3 Facial expressions using the novel eyebrows

In order to understand my novel design of the eyebrow in detail, I show the eyebrow at different angles in small increments in Fig. 5.6; from left to right, they are “extremely up,” “up,” “slightly up,” “medium,” “slightly down,” “down,” “extremely down.” Thus, subtle differences in the angle of the eyebrow control the expression of emotional intensity. Furthermore, the main strength of my novel design is that the eyebrow shape can be continuously manipulated to express “changes” in emotion with small movements. For example, it can be difficult to identify each emotion in the two images of “medium” and “slightly down”. Some people may perceive “slightly down” as a neutral emotion, while others may perceive it as concentrated. However, by continuously changing the angles e.g., from “medium,” to slightly down,” it is possible to express changes in emotion through slight differences that cannot be expressed by the static eyebrow shape alone or large dynamic movements. Similarly, the expressions of other slight emotional changes are achieved in the control in other angles.

The target position of the eyebrows and the velocity profile to reach it can be controlled by the speed of reeling the wires. This allows the robot created in this study to control the speed of facial expression changes, which is important in expressing vitality forms.

Also, I show the difference in appearance between my novel wire-driven eyebrow and the LED-based eyebrow on the conventional iCub in Fig. 5.7. In each technology, the eyebrows were positioned “extremely up,” “up,” “down,” and “extremely down, respectively. One of the key differences in the appearance of each eyebrow technology is the way the eyebrow shape is changed. My novel technology changes its eyebrow shape by operating the slider on the inner eyebrow, while conventional LED-based technology changes its eyebrow shape by turning on different LEDs and moving the entire eyebrow vertically. Since the LED-based eyebrows use such a method, each eyebrow shape is used for one or more facial expressions in the conventional iCub, as presented in Fig. 5.8. In detail, the “extremely up” positioning is used for surprise and fear, the “up” positioning is used for sadness, neutrality, and happiness, and The “extremely down” positioning is used for angry and disgusted facial expressions. Therefore, it is difficult to achieve subtle facial expression changes with the eyebrows in conventional LED-based technology.

5.5 Discussion

In this study, the expression of vitality forms was realized by realizing speed changes in the facial expressions of the iCub robot head, especially in the movement of the eyebrows that have the potential to be placed in a car and airplane. Also, this richer facial expression with continuous position and velocity changes should complement the missing elements of social signals in the conventional iCub robot head, thus enhancing social presence.

To realize the expression of vitality forms, I introduced a wire-driven mechanism for elastic material manipulation to control the eyebrow by adopting methods from surgical robotics, where soft robotics is increasingly being used. Conventional surgical robots are designed for cylinders with a diameter of 5 mm or more, but here I also targeted diameters of 5 mm or less. Surgical robots are manufactured in a subtractive manner to maintain high precision and strength. On the other hand, in 3D printing additive manufacturing, which I used, stability issues are associated with constraints such as minimum wall thickness, nozzle size, and temperature. Even with such restrictions, I generated and manipulated my small eyebrow structure. Therefore, with a better manufacturing procedure, I should control the eyebrows with much greater accuracy.

In addition, with the proposed prototype, I gave evidence of the feasibility of the new hardware design for continuous and speed-changeable eyebrow movements and direct shape-changing of a flexible eyebrow without manipulating the robot's skin. This result is a major step forward in researching robots that can produce vitality forms and subtle facial expressions in facial expressions. Accordingly, this opens the possibility to experiment with communication with the expressions, which has been a challenge so far in HRI research.

However, it is the limitation of the study that I have not yet conducted experiments on how my novel eyebrows impact humans with cognitive tasks. In particular, I need to investigate the propagation of vitality forms through continuous shape and velocity changes in the eyebrows and their impact on cognitive tasks. Moreover, to assess the details of the impact on humans, it is necessary to analyze whether slight changes in the novel eyebrows can convey the same emotional changes that are conveyed by slight changes in the human eyebrows.

Moreover, there are some limitations from a mechanical point of view. First, the design in this study is a prototype of a wire-driven eyebrow, replicating the straight shape of a human eyebrow, which is relatively easy to design mechanically. However, the actual shape of the human eyebrow is not always perfectly straight and has different angles depending on the person. It is necessary for the future to be able to control these different initial eyebrow shapes with wire-driven eyebrows freely. Second, the eyebrows created in this study are designed to show the convex and concave shape and the color of the elastic material to pass the wires. In order to reduce the mechanical discomfort, it is essential to cover it with some softcover and change the texture or color of the softcover to match the human's preferences better.

Furthermore, I did not thoroughly verify that the outer end of the eyebrow moves simultaneously with the shape change of the eyebrow. Although the inner eyebrow is a passive slider with one degree of freedom in the vertical direction, depending on the combination of movements, the eyebrow may change its shape differently from that of a human. I still need to analyze the movements and improve the mechanism.

Finally, I have reproduced vitality forms in facial expressions by allowing continuous changes in shape and velocity, but I recognize that changes in facial expression are not limited to the eyebrows. Although the replication of wrinkles is also one of the major factors, I need to carefully plan the next improvement, possibly avoiding the uncanny valley effect. On the other hand, manipulation of the mouth is crucial for expressing emotions, and by adding subtle changes in the mouth, it should be possible to create subtle facial expressions guided by mouth movement and with more variation in combination with the eyebrows.

5.6 Conclusion

Future work is to verify whether this robotic head can effectively support cognitive tasks with the knowledge gained in Chapters 3 and 4 through experiments. Then, it will realize effective applications that can be installed in confined spaces for cognitive tasks.

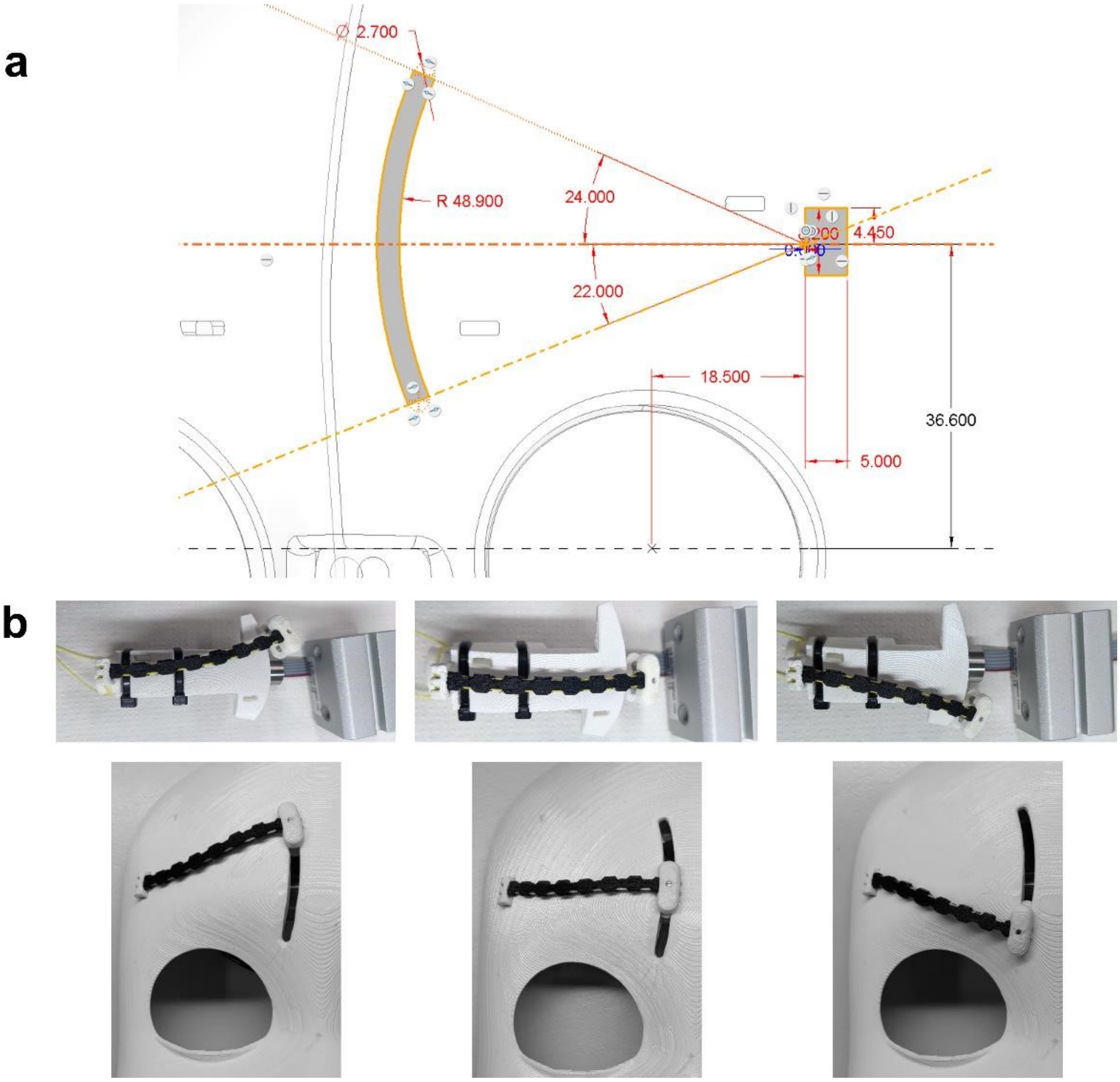

Figure 5.4: **a.** Limitations in the iCub face cover for the precise eyebrow movement, **b.** View of the implemented eyebrow mechanisms on the iCub front cover with and without the face cover and their comparative outcomes with facial expressions. The three positions of the eyebrow from left to right are maximum upward, medium, and maximum downward inclination for both technologies.

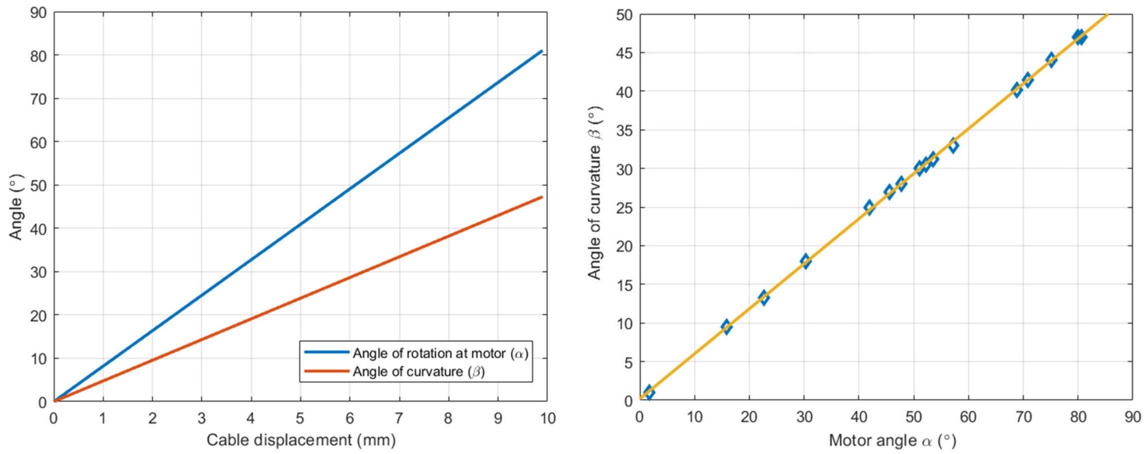

Figure 5.5: Comparative results between the theoretical calculation and practical data for two measures: a) angle of curvature of the eyebrow (°) and b) motor angle (°)

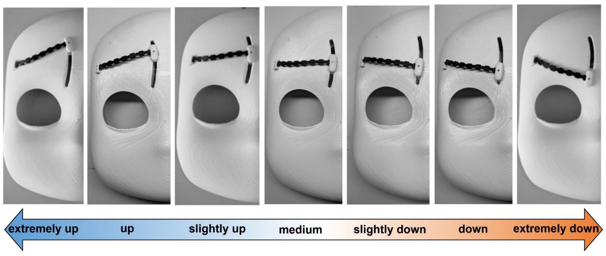

Figure 5.6: Facial expressions comparison according to the angle of the novel wire-driven eyebrow. The position of the eyebrow from left to right are “extremely up,” “up,” “slightly up,” “medium,” “slightly down,” “down,” “extremely down.”

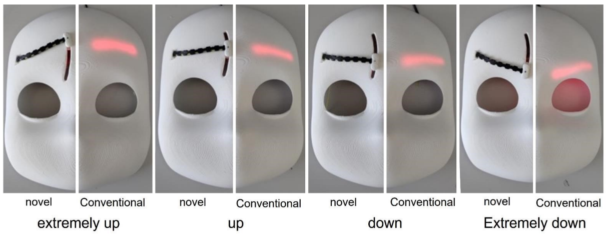

Figure 5.7: Facial expressions comparison between the novel wire-driven eyebrow and the conventional LED-based eyebrow on the iCub robot face. The position of the eyebrow from left to right are “extremely up,” “up,” “down,” and “extremely down.”

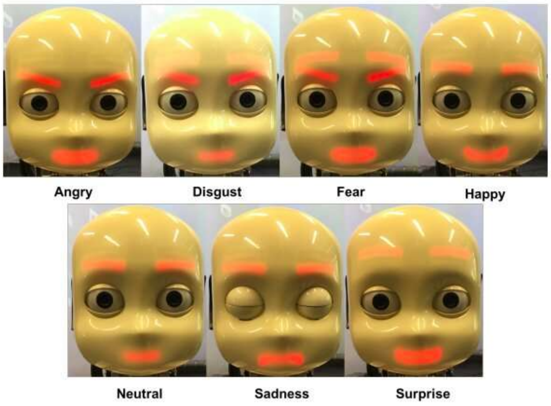

Figure 5.8: Conventional facial expressions of the iCub robot head.

Chapter 6

General discussion

The research objective of the thesis is to clarify the impact of social robots on cognitive multitasking and their principles and to provide a possible way through the development of hardware to apply social robots to industries such as automotive.

In chapter 2, I have developed the MATB-YARP, which can communicate with the iCub, a widely used social humanoid robot in research, and the Multi-Attribute Task Battery (MATB), a computer-based task designed to assess operator performance and workload. The scientific contribution of this is that it has made it possible to synchronously acquire data on social robot behavior and human behavior via YARP by improving the MATB, which had previously been difficult to record data in sync with other data. The MATB-YARP has enabled us to measure cognitive task performance with social robots even when new experimental conditions are prepared in the future. Thus, this system provided one of the basis for further research on collaborative cognitive multitasking with social robots.

In chapter 3, I evaluated the effects of social robots on cognitive tasks, which was one of the reasons that led to the development of the social robot head in chapter 5. It was found that the social robot improved performance on a cognitively demanding task requiring short-term memory and had a relaxing effect on people compared to the non-social robot. In contrast, the nonsocial robot was found to be more effective in improving responses to a simple reactive task. This study suggested that, depending on the characteristics of the task, robots should choose whether to use social signals in their behavior or behave mechanically. The scientific contribution of this study is that it is the first experiment to evaluate the impact of social robots on cognitive multitasking with MATB which is expected to have applications in driving and piloting tasks. This study takes a step forward in the evaluation of the impact of social robots on cognitive tasks, which had previously been done with relatively simple tasks such as the Stroop test and the Eriksen Flanker task [38, 40]. Taking this evaluation as a starting point, a multidimensional assessment of the impact of collaboration under various conditions in social robots would further advance how social robots should be utilized in automobiles and aviation, which are essential to our daily lives. A limitation of this study is that the tasks in the 5-minute experiment were divided into the social robot condition, in which the robot consistently used social signals, and the nonsocial robot condition, in which the robot did not consistently use social signals. Using the results of this study, when a robot efficiently supports complex multitasking, it may be able to determine whether or not to use social signals to support humans efficiently as each event in each task occurs. However, since the impact of the robot's behavior changing with each event has not been fully clarified, it is necessary to evaluate whether humans accept the changes in behavior and support style and whether the way is truly efficient through experiments.

In chapter 4, I evaluated the effects of social robots with different vitality forms on cognitive tasks, which is one of the reasons why I considered eyebrow velocity changes for facial expressions in the development of the social robot head in chapter 5. The gently behaving social robot improved performance on cognitively demanding tasks that require short-term memory, as well as on a tracking task that requires continuous focus. It was also found to relax people and to make their facial expressions more positive.

The scientific contribution of this study is that it was the first to evaluate how social robots should behave to influence cognitive multitasking, and took further forward previous research that had mainly compared a robot with social signals and without. This study also bridged the gap between mirror neuron research relating to vitality forms and psychological and behavioral research on social interaction robots and is important from both perspectives. In addition, evaluating the impact of vitality forms on MATB, cognitive multi-tasks will be helpful in practical applications to determine how to behave effectively when a robot communicates while a human is driving a car.

A limitation of this study is that the tasks in the 5-minute experiment were divided into two conditions: one with consistently gentle behaviors and one with consistently rude behaviors, similar to the experiment with and without social signals in chapter 3. Using the results of this study, social robots may be able to support more efficiently by determining whether or not to support using gentle behaviors for each event of each task individually as it occurs.

In chapter 5, I developed a novel hardware that has the potential to be mounted in a car and airplane based on the results of chapter 3 and 4. Due to the spatial constraints in cars, I chose to eliminate the torso from the humanoid robot iCub and place a social robot head as one of the possible solutions. However, the loss of the torso reduced the social presence, and the loss of the hands and arms reduced the means of expression. Therefore, I developed novel wire-driven elastic eyebrows with two objectives: 1) to preserve sufficient social presence and 2) to enable the expression of vitality forms. The novel eyebrows enabled continuous shape change and velocity change control, thereby solving these two problems. This novel hardware is important because it enables us to experiment with fine changes in facial expressions and behaviors related to vitality forms, which had not been possible to experiment with in social robot interaction research including cognitive tasks.

The scientific contribution of this study is that it has provided one of the ways to utilize social robots that express social facilitation effects and vitality forms in confined spaces such as cars, and one of the novel hardware solutions for robot facial expressions. The novel hardware allows us to place the robot head in a real confined space in a car and evaluate how effective it would be in a real car driving task. Then, the hardware provides a foothold for the industrial application of social robots in the real world with the evaluation.

A limitation of this study is that it has not yet finished evaluating the impact of the robot with the developed eyebrows on humans. Specifically, it is essential to examine the impact of the hardware on human cognitive multitasking performance from the robot's social presence and vitality forms changes.

Generally, the scientific contribution of this thesis is the clarification of aspects of the basic principles of hardware that manipulate social signals including social robots for real-world applications such as driving tasks. In particular, I focused on cognitive multitasking, which is an inevitable activity in the real world, and conducted an evaluation of the impact of social interaction on robots in general, as well as a more in-depth evaluation of the impact of differences in the way of social behaviors. These findings have strengthened the possibility that hardware that utilizes social interaction is effective for driving cars and airplanes. Thus, this thesis proposes the importance of the supports that utilize social signals, rather than mere functional supports such as caution in recognizing surroundings, lane keeping, or autopilot. A limitation of the thesis is that the studies mainly focused on the basic principles of the impact of social robots on cognitive tasks and the impact of social robots on one of the application areas, the car driving task, has not been fully clarified. For example, in actual driving tasks, there are a wide variety of cognitive events that occur, such as intersections, vehicles ahead, vehicles around, pedestrians, white lines, navigation, emergency vehicles, etc., and each event has different characteristics. Therefore, it is needed to evaluate the impact of social robots on these types of events. Meanwhile, concurrently with my work on the thesis that began in 2019, a study employing a driving simulator was conducted on heavy truck drivers by Fank et al. in 2021 [149]. Fank et al. demonstrated that truck drivers were more inclined to stay in their lane when interacting with a socially interactive and embodied robot agent compared to when interacting with a non-embodied agent. Therefore, it is crucial to integrate my research findings with other studies utilizing driving scenarios for future research.

Chapter 7

Towards the application of social interaction to AD and ADAS

Finally, in this chapter, I provide my views on the practical application of social interaction in cars for AD (Autonomous Driving) and ADAS (Advanced Driver-Assistance Systems).

7.1 Placing a social robot or making a social car

My thesis proposed one solution, which is placing a social robot in a confined space inside a car, but I do not limit other means to real-world applications. Especially as hardware that utilizes social interaction, there could be a means for humans and cars to communicate socially by defining the car itself as a social entity handling social signals. However, it is true that different characteristics arise from each approach, placing a social robot or making a car itself as a social entity. The former approach could maintain a similar form to conventional humanoid robots and enable collaboration through eye contact and mutual gaze like Namida [35] or AIDA [32]. However, it would also require careful design to ensure that it does not occupy interior space or obstruct the driver's field of view, necessitating consideration of its placement. For example, Tanaka's study utilizing RoboHon [150], and the previously mentioned Namida [35] and AIDA [32], all placed on the dashboard, but it is not the only solution. In particular, it is necessary to consider the location and communication method of the social robots so that they do not obstruct the view of the driver. Actually, it is not always possible to put the passenger next to the driver as in my study or the campaign of Sophia with Audi's self-driving car [151], but the placement is more natural if one wants to establish a relationship with a friend or spouse in the passenger seat. In case it is difficult to place a social robot next to the driver, it can be placed in the front or rear of the car, or even on the roof. Such placement may change the impression of the robot's role and relationship with the driver, potentially affecting driving performance and trust in the robot.

On the other hand, the latter would take advantage of the original hardware of the car, allowing for effective use of the interior and exterior design. For example in car frontal design, studies have been conducted that consider the appearance of the car as an anthropomorphic face while the context of the studies was consumer purchasing behavior [152, 153, 154]. In the context of consumer research, Windhager showed that the masculinity and maturity of the face vary with the frontal design of the car [154]. However, depending on how one defines the face of the car, if we define the front of the car as the face, eye contact can be made with pedestrians or other drivers outside the own car [155, 156, 157, 158], but cannot be made with its driver inside the car. Furthermore, when we step into the body of a social being, it creates a connection that humans rarely experience in the past and this relationship may provide a sense of being physically protected by the social being in her/his body. Moreover, when the "face of the car" is displayed on the dashboard or other parts inside, careful consideration from a hardware perspective is needed on how to establish eye contact with the driver and enable mutual gaze with objects both inside and outside the car. Furthermore, it requires careful hardware design to make sure it convinces that it is the "face of the car" rather than a separate entity.

Given these characteristics, it becomes extremely important to clarify how the insights developed in social human-robot interaction research can be applied through repeated prototyping and evaluation.

7.2 Trust for AD and ADAS with social interaction

Whether placing a social robot inside a car or making the car itself into a social entity, when it comes to elevating driving assistance and autonomous driving into a form of social communication beyond mere functionality, it is essential to consider not only functional trust but also trust for social entities. Hoff et al. have surveyed trust across various research fields, including psychology, sociology, philosophy, political science, economics, and human engineering, and they state that a common and vital element in the concept of trust is the existence of both a truster and a trustee [159]. While the concept of trust is often applied to human relationships, people also use the term"trust" when it comes to machines. In the context of automation, the trustee is a system that performs a task with some motivation, typically based on the intended use by the designers, and trust hinges on whether this is executed as intended. Lee and See defined trust in the context of automation as an attitude in situations characterized by uncertainty and vulnerability, where the system provides assistance in achieving individual goals [160]. From this perspective, in the context of driving assistance and autonomous driving systems, trust can be seen as the driver's belief in how reliably the system can navigate urban areas, country roads, and other terrains safely. On the other hand, when extending the trust from "trust in automation" to "trust in artificial social entities," such as social robots, the elements of trust that originally applied to "interpersonal trust" come into play. In other words, when artificial social entities are perceived as not just objects but as entities that socially understand and act within our world, we treat them not only as machines but also as individuals. Sweeney also noted that one factor in trusting social robots is their ability to mimic human social behavior [161].

Considering trust among humans reveals distinct characteristics not present in automation. For example, Holton pointed out that ‘In cases where we trust and are let down, we do not just feel disappointment, as we would if a machine let us down. We feel betrayed [162].’ Also, according to O’Neil, trust is associated with gratitude [163]. Furthermore, Coeckelbergh argued that what promotes trust is not what social robots actually are, but how they appear [164]. Anzabi and Umemuro showed that active and empathetic listening attitudes displayed by social robots enhanced trustworthiness [165]. When applying these perspectives to driving support, it becomes an issue that should be handled with extreme care. These suggest the possibility that the appearance and behavior of social cars or robots can also influence trust. In other words, they imply the potential to adjust trust, and if effectively utilized, it may be possible to prevent over-trust and distrust.

In summary, trust in artificial social entities capable of social interaction, such as social robots and social cars, is influenced by various factors related to trust in human relationships, such as emotions, empathy, physical commonality, gender, culture, facial expressions, eye contact, and mutual gaze. The use of social interaction in the context of driving assistance and autonomous driving is altering the dynamics of interaction compared to traditional automation relationships, and it has the potential to affect trust, mental workload, emotions, and so on. Therefore, research on AD and ADAS with social interaction needs to continue expanding in the future.

Chapter 8

General conclusion

Overall, my PhD thesis marked an essential step forward in basic research to evaluate the impact of social robots on cognitive tasks, as well as toward industrial applications. I sincerely hope that further research will be conducted from various perspectives in the future and that scientific progress and the potential for industrial applications will be further expanded.

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