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Help-Estimator: Robot Requests for Help from Humans by Estimating a Person's Subjective Time

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Abstract In human-robot cooperation, it is effective for a robot to ask a human partner for help to reduce the time required for a task. However, the person might not be able to help the robot if she or he is engaged in something else. In this study, we focused on the person's subjective estimation of the time for a task and investigated its effect on the likelihood of agreeing to help the robot. For this purpose, we developed a Help-Estimator system that decides whether the robot should request help by considering the required time for both the person and the robot to finish their tasks. We conducted an experiment to evaluate such help requests that incorporate the human's subjective time estimation for a task. We found that appropriate timing for requesting help, as estimated from the person's viewpoint, increases the likelihood of the person helping the robot and improves the person's impression of the robot as a partner.

Keywords Human-robot interaction · Human-robot cooperation · Help request

1 Introduction

Social robots provide services in real environments such as shopping malls [1], museums [2,3], and airports [4]. We expect such robots to be sociable and cooperative, and not merely communicative. However, further improvements will be needed to achieve actual human-robot cooperation. For example, a person and a robot may clean a room together. One of the benefits of using a cooperative robot is the time saved. [5] suggested that cooperative work between a human and a robot can be evaluating by measuring the idle time while they perform a task. There are various research works on improving such cooperative work by reducing the task execution time. [6,7] proposed an interaction design that enables the robot to help the person proactively to reduce the task time. [8] proposed a system that schedules the robot's behavior to help the human partner smoothly without the robot being idle. Although these studies were intended to make the robot help the human, there is another way to reduce the cooperative task time—i.e., the person can help the robot. Hence, this paper deals with a situation in which a robot requests help from a human partner to reduce the required time in a human-robot cooperative task.

Indeed, some previous works studied the behavioral design for a robot to be helped by a person [9,10]. For example, it is important to design what the robot says [9] and how it initiates the interaction with a person [10]. In these studies [9,10], the timing for the robot to ask for help was based on a situation in which the robot could not perform its own task by itself. However, the required task execution time can also be reduced by asking the person for help even if when the robot does not have to deal with a setback in its own task. This leads to a question of whether people would help a robot even when it seems able to perform its task on its own. For such situations, we assume that people's likelihood of helping a robot depends on their state and situation: the ability to perform the requested task, the time required for finishing the task, and their nature (kindness), because there is no requirement for a person to help a robot in a situation in which the robot can perform on its own. Moreover, as shown in Figure 1, the person may have reasons not to help the robot even

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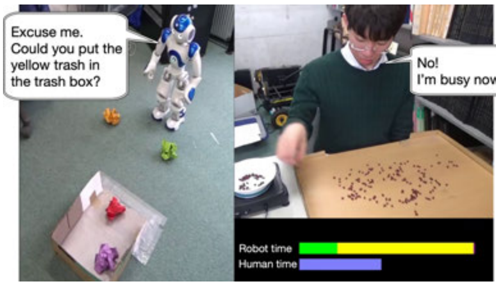

Fig. 1 Robot requesting help in human-robot cooperation: the robot asks the human partner for help to reduce the time required for the task (bottom right: required time estimated by the robot); the person, however, might not help the robot.

if the robot decides that requesting help will make the cooperative work more efficient. It is thus a key issue for the robot to estimate the nature and circumstances of people who are asked for help. In addition, if the robot requests help repeatedly, it might lose credibility as a partner. For the robot to become a good partner, it should stop requesting help from a person who does not seem receptive to it, even if the robot sincerely needs help.

In this paper, we investigate whether the likelihood of a person accepting a robot's request for help can be increased by having the robot consider the person's subjective estimation of the time required for a task. To investigate the effects of considering a person's subjective time estimation, we developed an experimental system called Help-Estimator, which finds a subtask for which a robot should request help from a human. Help-Estimator determines the subtask according to two processes: (1) it finds a useful subtask to reduce the time needed to complete a human-robot cooperative task, and (2) it deduces the human's likelihood of agreeing to help. A suitable subtask is found by calculating the amount of work to be completed in the overall task. The likelihood of agreeing to help is found by estimating how much busier the person feels in comparison to the robot during the cooperative task.

The paper is structured as follows. Section 2 describes related work in the context of human-robot cooperation and help requests from robots. Section 3 describes a preliminary case study that we conducted to investigate how people decide whether to help a robot, and it explains the problem that we address in this study. Section 4 describes the Help-Estimator system used in the experiment. In particular, it explains how Help-Estimator finds a suitable subtask and estimates the likelihood of the person agreeing to the robot's help request. Section 4 also explains how the robot assesses two time periods: the time that it spends doing its own task, and the time that humans spend doing their own task. Section 5 explains our experiment and hypotheses. Section 6 reports the experimental results and evaluates them in terms of the person's likelihood of helping the robot and the robot's impression on the person. Section 7 discusses the results and describes the limitations of this study. Finally, Section 8 concludes the paper and mentions future work.

2 Related Work

2.1 Human-Robot Cooperation

Increasing the efficiency of human-robot cooperation is critical in the human-robot interaction field, and there have been various research works on this topic. For instance, Hoffman proposed metrics to evaluate the fluency of collaboration [5]. Other works apply rational actions to achieve smooth collaboration. For example, collaboration can be facilitated by having robots proactively assist people [6] by speculating on their intentions [7][11] and taking understandable actions [12]. A robot's actions can be scheduled to adapt to the human partner and thus reduce the human's idle time [8]. Collaboration can be improved through task planning by using a daisy graph [13] and learning of human user models by using MOMDP [14]. Additionally, team performance can be improved by having a robot explain its own behavior [15].

Despite many such approaches to facilitate human-robot cooperation, there has been no research on reducing the duration of a cooperative task by having people help robots with their tasks instead.

2.2 Robot Asking for Help

In human-robot cooperation, robots typically support people; however, there are situations in which a robot cannot perform its given task. In such a situation, the robot must ask people for help to accomplish its task. For example, the robot might not be able to achieve the task [16] or reach its destination [17] on its own.

Many research works have studied the behavioral design of a robot asking people for help. For example, researchers have studied speech [9] and nonverbal behavior [18] as methods of requesting help. Additionally, there are studies on initiating interactions [9], promoting the attitude in interactions [19], and adjusting the interactive timing [20] when robots request help. To investigate whether people will help robots, researchers have observed human reactions to

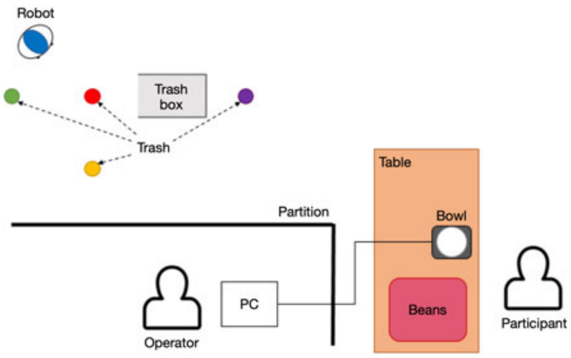

Fig. 2 Illustration of the preliminary case study

robot malfunctions [21] and failures [22]. In addition, empathy toward a robot encourages people to help it [23]. From the viewpoint of social psychology, Cameron explored a model of cooperation in which humans help robots [24]. Moreover, a robot that made errors was revealed to be more likable than a robot that performed perfectly [25]. This result suggests that a robot's help request probably does not make a bad impression on humans even when it cannot perform its task.

Other related works have focused on situations in which a robot asks for help from a nearby person who is not currently doing her or his own task or in which a robot's task is part of a cooperative task with a person. In such situations, there is no need for the person to interrupt her or his own work to help the robot. In contrast, in this research we focus on a situation in which a robot and a person work on a cooperative task but separately handle their individual tasks, with no requirement for the person to help the robot. For example, suppose that a person and a robot are cleaning a room together. The person might consider the robot's request for help to have merit, because if it gets help with a task that is time-consuming on its own, the cooperative task (e.g., cleaning) can be finished sooner. For such situations, to the best of our knowledge, no studies have investigated the robot's timing in asking for help by considering the person's subjective estimation of the time required for the task.

3 Case Study

To investigate how people decide to help robots, we investigated a preliminary case study with four participants.

3.1 Setting

Figure 2 shows the environment of the case study. The robot's task was to put four items of differently colored trash in a trash box, while the human participant's task was to put tiny beans in a bowl. The number of beans was adjusted so that the participant could finish her or his task before the robot could finish its task. The goal was to finish the cooperative task early, which required the robot to ask the participant for help to reduce its task time. When the participant had put all the beans in the bowl and all the trash was in the trash box, the trial was finished. To avoid errors by the robot, we used a Wizard-of-Oz-type scenario in which an operator manipulated the robot remotely from behind a partition so as not to be seen by the participant.

Before starting the case study, we gave the following instructions and information to the participants.

- We described the case study and the task's termination condition.
- We explained the cooperative task's goal to have both the participant and the robot finish their tasks early.
- During the task, the robot asked the participant to help by putting trash in the trash box. The participant could decide whether to help the robot. If the participant decided to help the robot, then she or he immediately stopped the individual task and helped the robot. If not, the participant ignored the robot and continued her or his own task.
- Neither the participant nor the robot intervened in the other's task unless the robot asked for help. That is, even if the participant finished the individual task earlier, she or he was not to help the robot unless it asked for help. We also informed the participants that they should decide whether to help the robot according to the goal of having them both finish their tasks early.

After receiving the instructions, the participants started the task. The timing of when the robot picked up each trash item and asked for help was decided in advance, as follows: when the robot put the red trash item in the trash box, it asked the participant to put the purple item in the box; then, when it approached the yellow item, it asked the participant to put the green item in the box. If the participant did not agree to pick up a trash item, the robot did not ask her or him to pick up that trash again. Thus, we observed whether the participants picked up the two trash items for which the robot asked for help. After each trial, we interviewed the participant and asked why she or he did or did not help the robot.

3.2 Results

All four participants responded to the first request for help and picked up the purple trash item. However, none of them responded to the second request to pick up the green item. All four participants' reasons for these decisions were related to their subjective time estimations. The reason for helping the robot was that "the purple trash item was far from the robot" or "the robot seemed to be taking more time than me." Similarly, the reason for not helping the robot was that "I thought I was taking more time than the robot" or "I hoped the robot would work harder." These reasons indicate that each participant decided whether to help the robot according to the estimated time to finish her or his own task. The key point is that the time here was not the actual time but the participant's estimated time according to a subjective perspective.

3.3 Problem to Solve

The case study results indicated that people did not always help the robot even when it asked for help. Therefore, it might be a waste of time for the robot to request help when the person seems unwilling to help. On the other hand, if the robot only requests help when the person seems likely to help, it can avoid wasting time on fruitless requests.

As described above, we assume that people decide whether to help a robot according to their subjective estimation of the time needed to finish a task. Thus, in a cooperative task, if the robot can estimate the person's subjective estimation of the time to finish her or his task, it can avoid asking for help when she or he is unlikely to help.

Various works in psychology have examined the perception of time flow (reviewed in [26]). In the human-robot interaction field, [27] focused on the effects of people's emotional states on time perception and proposed a robot that predicts how each person experiences the flow of time and accordingly prioritizes tasks requested by humans. However, there is no work on robots deciding whether to ask for help according to a human's subjective time estimation for a task.

To investigate the effects of a robot incorporating a person's subjective view of the time to finish a task in deciding whether to request help, we first need a method for a robot to estimate how long a person thinks it will take to finish a task and to decide an appropriate time to request help.

Fig. 3 Example of a cooperative task

3.4 Example Environment for Cooperative Task

As a first step toward such estimation of task times, this paper focuses on the cooperative task used in the case study, as shown in Figure 3. We chose this task because it is easy to estimate the time required for each individual task by measuring the mass of beans in the bowl and the distances between the robot and the trash items.

4 Help-Estimator

In this section, we describe a proposed system called "Help-Estimator," which we developed to investigate the effects of incorporating a person's subjective time estimation for a task into the model of a robot that requests help. Help-Estimator enables the robot to ask a person for help by estimating the subjective time that the person estimates it will take to complete her or his own task. Help-Estimator has two functions: it chooses robot subtasks with a required time that can be reduced by getting help from the person (i.e., finding a suitable subtask), and it estimates the acceptability of a robot's request for help (i.e., estimating help request acceptability). The robot generates a help request depending on the estimated acceptability, which ideally means that the person will have time to help.

4.1 System Architecture

Figure 4 shows a schematic of Help-Estimator, which consists of two time estimation (TE) modules and one help module. The time estimation module based on the robot's viewpoint (robot TE module) estimates the time required for both the person and the robot to finish their own tasks, with the estimation based on their physical activities. The time estimation module based on the person's viewpoint (person TE module) estimates how long the person thinks it will take for she or he and the robot to finish their tasks,

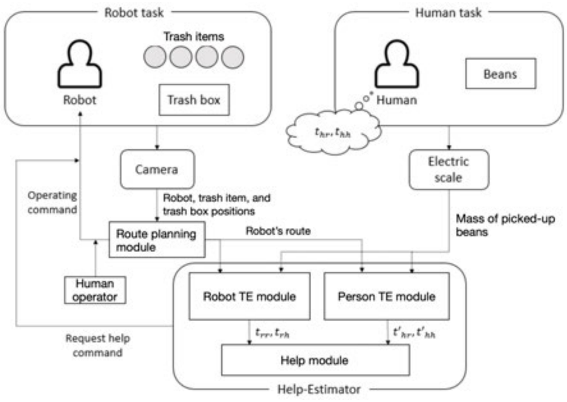

Fig. 4 Schematic of Help-Estimator

with the estimation based on her or his subjective viewpoint. Finally, the help module selects a subtask for which the robot should ask for help from the person, according to the time estimation by the two TE modules.

The robot TE module estimates the time from the robot's viewpoint by measuring the remaining physical characteristics of the individual tasks. First, t_{rh} denotes the time estimated by the robot for the person to finish her or his task. In the cooperative task used here, it is calculated from the remaining mass of beans and the average speed at which the person has picked them up. Second, t_{rr} denotes the time estimated by the robot for it to finish its own task. Here, it is determined by measuring the distances between the robot and the remaining trash items and the angles between the direction it is facing and the bearings to the items.

The person TE estimates the time from the person's viewpoint by using two estimation criteria for the progress of her or his own task and for the progress of the robot's task. The first criterion is used to estimate t_{hh}, which denotes how long the person thinks it will take to finish her or his own task. The second criterion is used to estimate t_{hr}, which denotes how long she or he thinks it will takes the robot to finish its task. We use t'_{hh} and t'_{hr} to denote the results of estimating t_{hh} and t_{hr}, respectively.

Both TE modules need information on the progress of the person's and robot's tasks. We measure the robot's progress by using a fixed-point camera to obtain the position coordinates of the robot, the trash items, and the trash box. We measure the person's progress by using an electric scale to obtain the mass of beans in the bowl.

Figure 4 also shows a route planning module, which creates the route for the robot to perform its task and sends commands to the robot to guide it along the created route. Note again that to avoid robot behavioral errors in the experiment reported here, the robot was operated by a human in a Wizard-of-Oz scenario.

4.2 Help Module

4.2.1 Finding Suitable Subtask

First, the help module chooses the robot's subtask for which it should request help. The candidate subtasks are selected according to the robot's viewpoint, which means that receiving help from the person should reduce the time for the robot to finish these subtasks. For example, in Figure 3, the subtasks correspond to the trash items. The robot's task time will be significantly reduced if the person throws away the item that is farthest from the robot.

Because the person and the robot perform their own tasks simultaneously, the time T required for the cooperative task is derived from t_{rh} and t_{rr}:

$$T = \max(t_{rh}, t_{rr}). \tag{1}$$

The help module also calculates the expected total time T_o if the robot requests help from the person for subtask o and she or he performs it instead of the robot:

$$T_o = \max(t_{rh} + h_o, t_{rr} - t_o + h_o). \tag{2}$$

Here, h_o denotes the total time for the robot to generate a help request for subtask o and the person to perform that subtask, and t_o denotes the required time for the robot to perform subtask o by itself.

Next, Ω denotes the subtask that minimizes the time required for the task when the person helps with it. The help module selects Ω according to the following equation:

$$\Omega = \arg \min_{o \in task} T_o. \tag{3}$$

When $T_\Omega > T$, the robot does not request help, because obtaining help with Ω would not reduce the overall task time.

4.2.2 Estimating Help Request Acceptability

After selecting a suitable subtask Ω, the help module decides whether the robot should request help for Ω. The results of the preliminary case study described in Section 3 indicated that the participants agreed to help the robot when they thought they could finish their task earlier than the robot could finish its task. Hence, we use this empirical result as a criterion for estimating the acceptability of a robot's help request, as follows:

$$t'_{hr} - t'_{hh} - h_\Omega > 0, \tag{4}$$

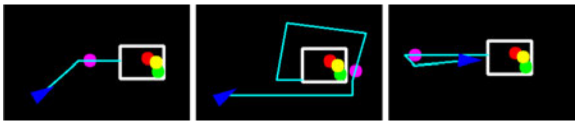

Fig. 5 Examples of the robot's routes

where h_{Ω} denotes the time it will take the person to help the robot with Ω. Thus, the robot does not request help when condition (4) is not met.

4.3 Robot TE Module

As described above, the TE module based on the robot's viewpoint estimates t_{rh} and t_{rr} by measuring the remaining physical characteristics of the person's task and the robot's task, respectively.

4.3.1 Estimating t_{rh}

The robot TE module estimates t_{rh} by estimating the remaining number of beans and using the average speed c for the person to pick up a bean. As the person picks up beans, c is updated according to the following equation:

$$c = \frac{n}{t}, \tag{5}$$

where n is the number of beans picked up, and t is the time from the start of the cooperative task. To obtain n, we place an electric scale under the bowl to measure the mass of beans picked up. Then, we estimate n from the mass by using the average mass of 100 beans.

Next, t_{rh} is calculated by the following equation, where N is the total number of beans to be picked up:

$$t_{rh} = \frac{N - n}{c}. \tag{6}$$

4.3.2 Estimating t_{rr}

Because the robot uses an algorithm to deterministically create a route to the trash, t_{rr} is determined according to the route distance D and the total turning angle Φ, which determine the total travel time due to the robot's walking and turning actions.

4.3.3 Creating Route

The route planning module uses Algorithm 1 to create a route ζ for the robot to put the trash items in the trash box. The route is defined as a set of points that are subgoals for the robot to reach. It guides the robot to a position behind each trash item to allow the robot to move the trash easily. Then, it guides the robot to the trash box.

Algorithm 1 generates ζ by combining a path from the robot to a trash item, generated by Algorithm 2, and a path from the trash item to the trash box, generated by Algorithm 3. Figure 5 shows examples of routes generated by these algorithms.

Algorithm 1 Creating the robot's route

```
function ROBOTROUTE
    ζ = {}
    for each trash item o do
        if o is in trashBox then
            continue
        else if o is target then
            if robot possesses o then
                ζ+ = routeToBox(o)
            else
                ζ+ = route(robot, o) + routeToBox(o)
            end if
        else
            ζ+ = route(trashBox, o) + routeToBox(o)
        end if
    end for
    return ζ
end function
```

Algorithm 2 Defining the route from *start* to *goal*

```
function ROUTE(start, goal)
    l: line segment from start to goal
    if l crosses trashBox then
        set path to detour to trashBox
    else
        path = {goal − start}
    end if
    return path
end function
```

Algorithm 3 Defining the route from *start* to the trash box

```
function ROUTETOBOX(start)
    goalLine: open side of trashBox
    if start.x < goalLine then
        path = {goalLine − start}
    else
        set path to detour to trashBox
    end if
    for p in path do
        set p to space in direction of p → next
        if route(p, p → next) passes o then
            add new point p∗ between p
                and p → next to detour to o
        end if
    end for
    return path
end function
```

4.3.4 Calculating Required Time

The required time t_{rr} for the robot's task is calculated from the generated route. Given $\zeta = \{p_0, p_1, ..., p_m\}$, where each point p_i is a two-dimensional vector, the total distance D and total angle Φ are calculated as

$$D = \sum_{i=0}^{m-1} dist(p_i, p_{i+1}), \quad (7)$$

$$\Phi = \sum_{i=0}^{m-2} |\arctan(p_{i+2} - p_{i+1}) - \arctan(p_{i+1} - p_i)|, \quad (8)$$

where $dist(p_i, p_{i+1})$ is the distance from p_i to p_{i+1}.

Finally, given the robot's velocity v and angular velocity ω, t_{rr} is calculated as follows:

$$t_{rr} = \frac{D}{v} + \frac{\Phi}{\omega}. \quad (9)$$

4.4 Person TE Module

The TE module based on the person's viewpoint estimates t_{hh} and t_{hr} by deducing how much progress the person thinks that she or he and the robot have made on their tasks. Thus, this section investigates how people subjectively estimate the time required for each task, and it develops models to more accurately estimate the expected time. We also verify that the models properly estimate a person's subjective sense of time for the tasks used here.

4.4.1 How People Estimate Time for Own Task

We conducted an experiment to investigate how people estimate the remaining time for their own task. We asked eight participants to each pick up 200 beans, and we measured the time for each to perform the task. Before starting the task, we asked the participants how long they thought it would take them to finish the task. Then, every 10 beans, we asked them to estimate the remaining time needed, and this was repeated until the task was finished. After the experiment, we asked the participants how they estimated the time required for the task.

The results indicated that the participants estimated the remaining time from the remaining number of beans. However, this estimation is different from the robot's estimation of t_{rh}, which is completely based on physical characteristics, even though the participants referred to the remaining number of beans. At the beginning of the task, they constantly decreased the estimated required time by a certain amount, regardless of their initial expectations. Then, they corrected the expected time several times when only two-thirds to one-half of the beans were left, because they thought the task was taking more or less time than they had expected. After correction, they decreased the time by a certain amount again. Finally, they correctly determined the required time when about 30 beans were left.

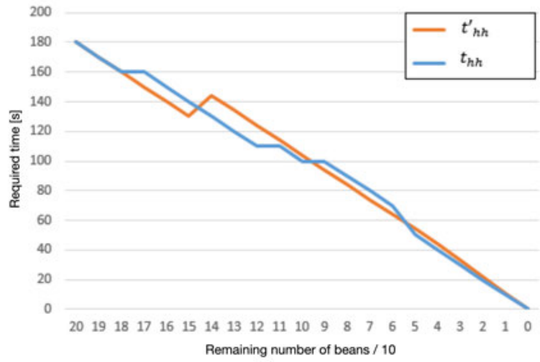

Fig. 6 Comparison between t'_{hh} and t_{hh} for one participant

4.4.2 Estimating t_{hh}

From the above findings, we defined a function $pred\_t_{hh}(n)$ that estimates t_{hh} in terms of n, the remaining number of beans, as follows.

$$pred\_t_{hh}(n) = \begin{cases} t_H - v_h(N-n) & n > \tau \\ \frac{t_H - v_h(N-\tau) - t_{rh}}{2} + t_{rh} & n = \tau \\ pred\_t_{hh}(\tau) - v_h(\tau - n) & 30 < n < \tau \\ n \cdot pred\_t_{hh}(30)/30 & n < 30 \end{cases} \quad (10)$$

Here, N is the total number of beans, t_H is the initial time that the person expects before starting the task, and v_h is the time taken to pick up one bean. Finally, τ is the timing to adjust the expected time, as the participants did in the experiment described in subsection 4.4.2; we set $\tau = 2N/3$.

4.4.3 Accuracy of Expected t'_{hh}

Figure 6 shows a graph that compares t'_{hh} to t_{hh} for the data obtained in the experiment described in subsection 4.4.2. The graph indicates how well Equation (10) estimates a person's subjective perception of the time required for the task of picking up beans. The average error was ±25.57 s, and the correlation was 0.947. Thus, because of its accuracy, we use this equation as the person's criterion for estimating the progress of her or his own task.

4.4.4 How People Estimate Time for Robot's Task

We also investigate how people estimate the remaining time t_{hr} for the robot to finish its task, and we develop a model to estimate t_{hr} and verify its accuracy. We again conducted an experiment, in which five participants observed the robot performing its task and estimated how long it would take to finish. As in our preliminary case study, the robot was operated by a human in a Wizard-of-Oz manner. The robot walked and stopped once every four steps that it took (we refer to this as a step set). In each step, the robot could take one of the following actions: walk forward, walk backward, turn left, or turn right. To avoid giving the participants an obstructive effect due to fluctuations in the robot's action timing, it accepted a command from the human operator every 4 seconds. By having the robot's actions based on a constant interval, the participants could more easily estimate the time required for its task.

Before starting the task, we asked the participants how long they though it would take the robot to finish the task. Then, every time the robot performed one step set, we asked the participants to estimate the remaining time for the robot's task, and this was repeated until the robot's task was finished. After the experiment, we asked the participants how they estimated the time required for the robot's task.

The results indicated that the participants estimated the remaining time according to how far the robot moved in one walking step and how many degrees it turned left or right in one turning step. They decreased the expected time when there was no disruption in the robot's movement. On the other hand, they increased the expected time when there was a disruption, such as the robot performing differently from their expectation or trash kicked by the robot rolling away from its course.

The way the participants expected the robot's task time to be based on its movement is similar to the robot's estimation for its own task, as described in subsection 4.3.4. The primary difference is that the participants did not know the robot's exact route and thus used the speed of the robot's steps according to their subjective expectations.

4.4.5 Estimating t_{hr}

From the above findings, the person TE module uses the number of steps from the robot to the trash items to estimate t_{hr}. The total number of steps is calculated from the total distance and total angle for the robot to follow the route ζ.

Let D_z be the distance and Φ_z be the rotation angle along a line z that is a route between subgoals in ζ. The number of steps forward, s, and the rotation, r, are given by

$$s = \frac{D_z}{d}, \tag{11}$$

$$r = \frac{|\Phi_z|}{\varphi}, \tag{12}$$

where d is the distance that the robot can go forward in one step, and φ is the rotation angle that it can turn in one step. Then, the total number of steps, S, can be calculated as

$$S = \sum_{z \in \zeta} (s + r). \tag{13}$$

Let z_i be the route for the first subtask in the remaining path ζ. When the robot moves along z_i, we assume that there is no disruption in its actions. The person TE module decrements the number of steps from the initial value calculated by Equation (13). The module recalculates the number of steps if it becomes negative or the robot has to replan a new route because of an environmental change.

For instance, suppose that the person TE module has to recalculate the route and the number of steps when trash kicked by the robot rolls away from its course. Let p_r be the robot's position, p_t be the trash item's position, and θ be the robot's rotation angle. The person TE module judges that the robot kicked the trash off course when

$$dist(p_r, p_t) \cdot |\sin(\arctan(p_t - p_r) - \theta)| > robotwidth. \tag{14}$$

Here, t'_{hr}, which is the expected value of t_{hr}, is calculated as follows:

$$t'_{hr} = \frac{t_R}{S_0} \cdot S, \tag{15}$$

where t_R is the time that the person expected before starting the cooperative task, and S_0 is the number of steps calculated at the beginning of the task by Equation (13). Because the person intuitively considers the t_R value, $\frac{t_R}{S_0}$ is related to her or his subjective judgment.

4.4.6 Accuracy of Expected t'_{hr}

We conducted another experiment with four participants by using the same procedure described in subsection 4.4.6. In this case, however, we asked them to estimate the required number of steps instead of the remaining time, according to the above finding on how people estimate the time for the robot to finish its task. The results indicated that the average error

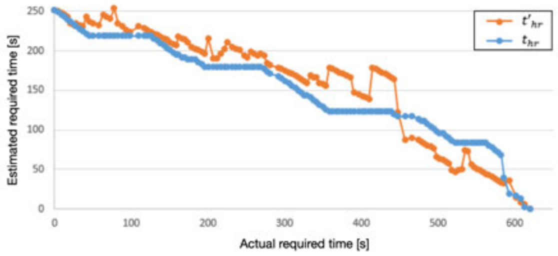

Fig. 7 Comparison between t'_{hr} and t_{hr} for one participant

in the estimation was ±5.47 steps, and the correlation between t'_{hr} and t_{hr} was 0.979.

In addition, we verified whether the remaining time can be estimated as well as the remaining number of steps. We asked two participants to estimate the required time t_{hr}. Figure 7 shows a graph that compares the actual t_{hr} and the estimated t'_{hr}. The average error was ±22.22 s, and the correlation was 0.942. Thus, because of its accuracy, we use Equation (15) as the person's criterion for estimating the progress of the robot's task.

5 Experiment

We conducted an experiment to investigate whether a robot that requested help by incorporating an estimation of a person's subjective time for task completion would receive more help. We also investigated whether this kind of help request gave a better impression of the robot than a request that did not consider the subjective remaining time estimated from the person's viewpoint.

5.1 Setting

We used the same cooperative task and environment shown in Figure 2. The human participant put beans in a bowl, while the robot put trash in a trash box. The task was complete when all the trash items were in the trash box and all the beans were in the bowl. There were four trash items, colored red, green, yellow, and purple, and 200 beans. During the task, at a time based on the participant's subjective estimation of the time to finish it, the robot asked for help from the participant to finish the task sooner.

The robot was operated by a human behind a wall instead of by the route planning module. The route planning module automatically generated a route and replanned it according to the locations of the trash items. Although the generated route was used to estimate the remaining time for the task, the robot's actions were selected by the operator to improve its behaviors for the task. Specifically, the operator made the robot deal with the trash items in the order of red, green, yellow, and purple. The timing was based on when the robot went to put the next item in the trash box after it had succeeded in putting the previous item in the box. Success was determined by a ceiling camera that recognized when a trash item was within the area of the trash box.

The participant put the beans in the bowl one by one. The mass of beans was measured by an electric scale placed under the bowl, and this information was sent to a computer. During the task, the robot asked the participant to help by putting a trash item in the trash box (e.g., "Excuse me. Would you put the purple trash in the trash box?"). The participant then decided whether to help the robot. If the participant decided to help the robot, she or he had to stop her or his own task and help the robot. Otherwise, the participant could ignore the robot's request and continue the individual task. When the ceiling camera recognized that a trash item for which help was requested was within the trash box, it was determined that the participant had helped the robot.

To motivate the participants to help the robot, we instructed them that the participant and the robot needed to finish the task early by working together. In addition, the participant and the robot were not to intervene in each other's tasks except when the robot asked for help; in other words, the participant was not to help the robot unless the robot asked for help, even if she or he had already finished the individual task.

5.2 Conditions

We performed the experiment with the following two conditions:

Help-Estimator: The robot requested help by using the Help-Estimator system to estimate both its own required time and the person's subjective estimated time.

NotPred: The robot requested help only by estimating the required time; it did not consider whether the person would accept a help request.

Thus, NotPred used only Equation (3) as the criterion for generating a help request, while Help-Estimator used both Equations (3) and (4).We compared the results under each condition to investigate whether predicting the person's subjective estimated time would increase the likelihood of obtaining help from the person.

5.3 Participants

We had 15 participants (12 men, 3 women; average age 23.8 years, $SD = 1.42$) in the experiment. We used a within-subject design and counterbalanced the order of the conditions.

5.4 Procedure

Beforehand, an experimenter gave the participants an outline of the experiment. They were informed that the goal was to finish both their task and the robot's task as quickly as possible. In addition, the participants were asked to observe the robot's motion and determine its speed and amount of movement. This observation was to make it easier for the participants to estimate the time required for the robot's task. The participants were also told that the robot would request help during the task. The experimenter told them how to handle the request but did not explain the condition that would prompt it.

Before starting the task, the experimenter asked the participants to estimate the time that they and the robot would require to perform their own tasks. The participants estimated the time by assuming that they and the robot would perform their own tasks independently of each other, without considering the case of helping the robot. The estimated times were used as t_H in Equation (10) and t_R in Equation (15). After the participants had estimated these times, they began the experiment.

During the task, the robot decided whether to ask for help each time it received an action command to move from the experimenter (every 4 seconds). When the Help-Estimator system judged that the robot should ask for help, it asked for help instead of moving. The robot waited 10 seconds for the participant to help; that is, it judged that it did not get help if the participant did not help within 10 seconds. When the participant did not help, the robot changed its status to receive the next action command. In this case, the robot did not change the target trash item on which to ask for help. Therefore, the robot sometimes asked for help on the same item several times according to the judgment of Help-Estimator. Note that the robot did not ask for help within 30 seconds of the task's start.

The participants worked through two sessions for each of the Help-Estimator and NotPred conditions. After each session, they answered a questionnaire to evaluate their impressions of the robot. Then, at the end of the experiment, they were asked to choose which robot they would prefer to work with between the two conditions.

5.5 Measurements

5.5.1 Objective Metrics

To investigate the acceptability of the robot's help request, we measured a help ratio, which we calculated by dividing the number of times that the participant agreed to help and moved the trash to the trash box by the number of times that the robot requested help.

5.5.2 Subjective Metrics

We used Godspeed [28] to measure the participants' perception of the robot. Godspeed measures a user's perception of a robot from the following five perspectives: anthropomorphism, animacy, likability, perceived intelligence, and perceived safety. Each perspective includes multiple questions with five-point semantic differential scales, where one indicates a negative perception and five indicates a positive perception.

In addition, we used the following seven questionnaire items to evaluate the impressions of the robot in the cooperative task and evaluated them on a seven-point scale ranging from 1 (disagree) to 7 (agree):

- Did the robot try to reduce the time required for the task?
- Did you rely on the robot?
- Did the robot depend on you?
- Did the robot make an effort?
- Was the robot cooperative?
- Was the robot friendly?
- Did the robot understand the situation of your task?

To evaluate the appropriateness of the timing of the robot's help requests, we used the following five questionnaire items and again evaluated them on a seven-point scale ranging from 1 (disagree) to 7 (agree).

- Did you feel reluctant when the robot asked for help?
- Did the robot ask for help in appropriate situations?
- Did you feel that the robot recognized the necessity of asking for help?
- Did you want to help the robot?
- Did the robot take your situation into account when requesting help?

Finally, as described above, we asked the participants to choose the robot they would prefer to work with between the two conditions.

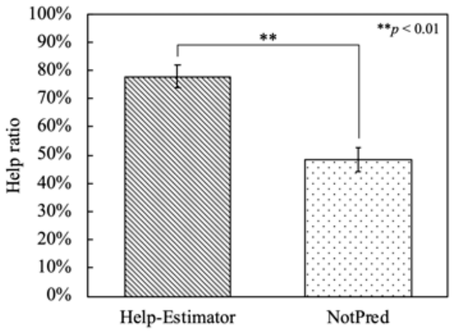

Fig. 8 Help ratio

5.6 Hypotheses

H1: The help ratio would be increased by estimating the person's subjective estimated time.

The participants were expected not to help the robot when they were busy with their own task. We thus expected that the help ratio would be higher for Help-Estimator than for NotPred, because the participants had to pause their own task to have time to help the robot.

H2: The impression of the robot would be improved by estimating the person's subjective estimated time.

Because requesting help without accounting for the person's likelihood to help would increase the number of times the robot makes requests, frequent requests would impair the person's impression of the robot's credibility. We thus expected that Help-Estimator would keep the number of help requests to the minimum necessary so that the robot would offer a better impression than under the NotPred condition.

6 Results

6.1 Objective Metrics

Figure 8 shows the help ratio results. We conducted a paired t-test and found a significant difference between Help-Estimator and NotPred ($t(14) = 3.60,\ p = 0.003,\ d = 0.928$) for the help ratio.

6.2 Subjective Metrics

Figure 9 shows the results for the Godspeed questionnaire. We conducted a paired t-test and found a significant difference between Help-Estimator and NotPred for all five perspectives: anthropomorphism ($t(14) = 3.25,\ p = 0.006,\ d = 0.839$), animacy ($t(14) = 3.02,\ p = 0.009,\ d = 0.780$), likability ($t(14) = 4.24,\ p < 0.001,\ d = 1.094$), perceived intelligence ($t(14) = 4.30,\ p < 0.001,\ d = 1.110$) and perceived safety ($t(14) = 2.23,\ p = 0.043,\ d = 0.576$).

Figure 10 shows the results for the questions on the impressions of the robot in the cooperative task. We conducted a paired t-test and found a significant difference between Help-Estimator and NotPred for the following six items: "Did the robot try to reduce the time required for the task?" (Help-Estimator > NotPred, $t(14) = 3.06,\ p = 0.009,\ d = 0.789$); "Did you rely on the robot?" (Help-Estimator > NotPred, $t(14) = 3.02,\ p = 0.009,\ d = 0.780$); "Did the robot make an effort?" (Help-Estimator > NotPred, $t(14) = 4.96,\ p < 0.001,\ d = 1.282$); "Was the robot cooperative?" (Help-Estimator > NotPred, $t(14) = 4.08,\ p = 0.001,\ d = 1.052$); "Was the robot friendly?" (Help-Estimator > NotPred, $t(14) = 3.33,\ p = 0.005,\ d = 0.860$); and "Did the robot understand the situation of your task?" (Help-Estimator > NotPred, $t(14) = 3.51,\ p = 0.003,\ d = 0.907$). We found no significant difference between the two conditions for the other item: "Did the robot depend on you?" ($t(14) = 1.79,\ p = 0.095,\ d = 0.463$).

Figure 11 shows the results for the questions on the appropriateness of the timing of the robot's help requests. We conducted a paired t-test and found a significant difference between Help-Estimator and NotPred for all of the items: "Did you feel reluctant when the robot asked for help?" (Help-Estimator < NotPred, $t(14) = 2.94,\ p = 0.011,\ d = 0.759$); "Did the robot ask for help in appropriate situations?" (Help-Estimator > NotPred, $t(14) = 4.51,\ p < 0.001,\ d = 1.166$); "Did you feel that the robot recognized the necessity for asking for help?" (Help-Estimator > NotPred, $t(14) = 2.58,\ p = 0.022,\ d = 0.666$); "Did you want to help the robot?" (Help-Estimator > NotPred, $t(14) = 4.96,\ p < 0.001,\ d = 1.281$); and "Did the robot take your situation into account when requesting help?" (Help-Estimator > NotPred, $t(14) = 4.36,\ p < 0.001,\ d = 1.126$).

Finally, regarding the participants' choice of which robot they would prefer to work with, 85% preferred Help-Estimator, while the rest preferred the NotPred robot.

7 Discussion

7.1 Implications

The results shown in Figure 8 support hypothesis H1. That is, estimating the person's subjective estimated time increases the probability of the robot

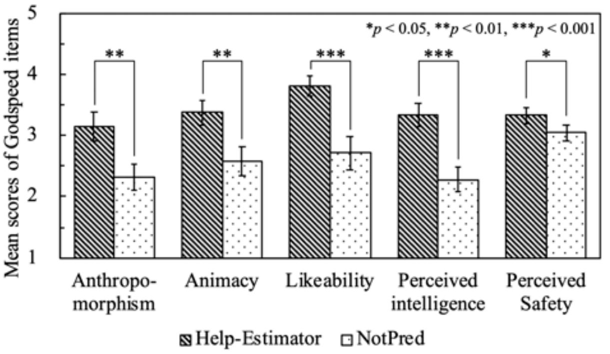

Fig. 9 Mean scores for Godspeed items (1: negative; 5: positive)

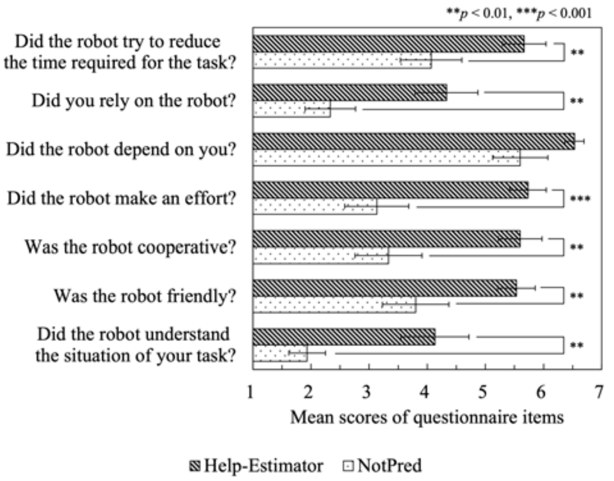

Fig. 10 Mean scores for questionnaire items on the impressions of the robot (1: disagree; 7: agree)

receiving help. Regarding why people did not help the robot, the reasons included not only responses such as "my task takes time" but also "I want the robot to try harder." Figure 10 shows evidence similar to these comments, indicating that the NotPred robot put in less effort than the Help-Estimator robot. Also, from Figure 11, the participants felt that the Help-Estimator robot requested help at a more appropriate time than the NotPred robot, and they preferred to help the robot equipped with Help-Estimator. We can conclude that the help ratio will increase if the robot works hard to some extent, rather than asking for help more often than necessary.

The results shown in Figures 9, 10, and 11 indicate that the Help-Estimator robot offered better impressions than the NotPred robot, which supports hypothesis H2. The better impression is also shown by the 85% of the participants who preferred the Help-Estimator robot. The reasons for this included opinions

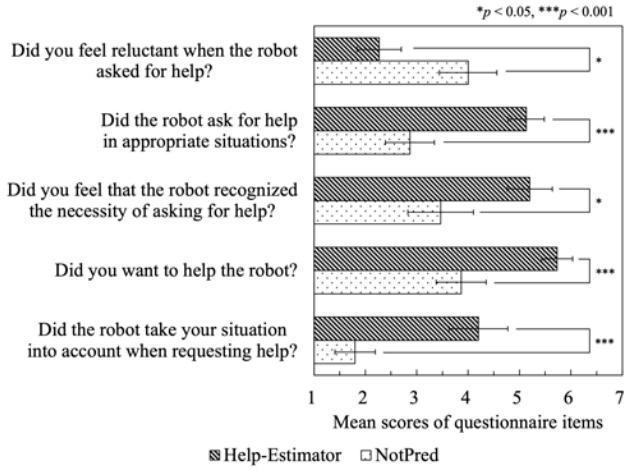

Fig. 11 Mean scores for questionnaire items on the appropriateness of the timing of the robot's help requests (1: disagree; 7: agree)

such as "I felt that the robot tried to finish the task earlier" and "the robot requested help while checking on my situation." Although 15% of the participants preferred the NotPred robot, even they always helped the robot. Some of them said, "I couldn't understand the difference between Help-Estimator and NotPred."

7.2 Effects of Other Possible Factors

In the experiment, we only focused on the person's subjective time estimation for the task. However, other internal factors such as expertise, trust, motivation, and engagement also could affect people's decisions on whether to help. To understand the effects of these factors, two coders categorized the answers from a free-description questionnaire on why the participants did or did not help the robot into the following five primary types: (1) subjective time estimation for the task, (2) robot's attitude, (3) robot's capability, (4) number of requests, and (5) other. The coding procedure was as follows. First, the coders categorized the descriptive feedback into the five types. Next, to test the interrater reliability we calculated Cohen's kappa; it was 0.679, indicating substantial reproducibility. Finally, the coders discussed the discrepancies in their categorizations and categorized the answers.

As a result, the percentages of categorized feedback were as follows: (1) subjective time estimation for the task, 63.8%; (2) robot's attitude, 10.3%; (3) robot's capability, 13.8%; (4) number of requests, 10.3%; and (5) other, 1.7%. First, there was much feedback on (1) the subjective time estimation for the task: e.g., "I thought if I helped the robot, we would finish the task more quickly," and "I didn't help the robot because my task didn't seem like it would end any time soon." This result indicates that the subjective time estimation was an important factor when the participants considered the robot's help requests. It also supports the experimental result that estimating the person's subjective time increased the probability of the robot receiving help.

There was also feedback related to the other factors. Some participants remarked on (2) the robot's attitude: e.g., "I helped the robot because it asked me to help after trying its best," and "I didn't help the robot because it didn't seem to be trying to do the task by itself." This result suggests that, in order to get more help from people, it is important to design a robot's behaviors so that it appears to be making an effort. This mental factor should be important in the context of human collaboration preferences, and we will need to investigate its effects in a future work. In addition, there were remarks on (3) the robot's capability: e.g., "I helped the robot because the trash was behind the robot and it was difficult for the robot to collect it," and "The trash was at the robot's feet and I thought it could collect the trash by itself." Although these remarks are difficult to clearly distinguish from the feedback on the subjective time estimation for the task, they suggest the effect of people's preconception of the robot's capability. We will also need to further investigate this point in the future. Next, there was feedback on (4) the number of help requests: e.g., "I helped the robot because it only asked me to help a few times," and "Once, I tried to ignore the help request because of my task situation, but the robot asked a few times and I reluctantly helped it." This type of feedback suggests a simple relationship whereby, if the robot asks for help many times, people will agree to help. On the other hand, this type of feedback sometimes indicated a negative impression, meaning that the robot should avoid frequent requests. Finally, the (5) other category included one remark: "I just wanted to help the robot."

7.3 Effects on Required Time to Finish Task

In the experiment, we did not compare the robot in the Help-Estimator and NotPred conditions to a robot that did not ask for help at all. To investigate whether and by how much the help requests reduced the required time to finish the task, we additionally gathered data from an experiment with five participants, in which the robot did not ask for help. Figure 12 shows the mean time required to finish the task when the robot did not ask for help, along with the times from the original experiment in the Help-Estimator and NotPred conditions. The results suggest that the robot's help requests reduced the time to finish the task, while the time differed little between the Help-Estimator and NotPred conditions. In our experimental setting, an increased rate of agreeing to help requests was not directly related to a decrease in the time to finish the task. We used a simple task to focus on the effects of incorporating a human's subjective view of her or his own task when a robot asks for help. In a more complicated or time-consuming situation, the rate of agreeing to help requests may affect the time to finish the task. Further research will be needed on what kinds of cooperative tasks will show efficient reductions in the required time when help requests consider a person's subjective time estimation.

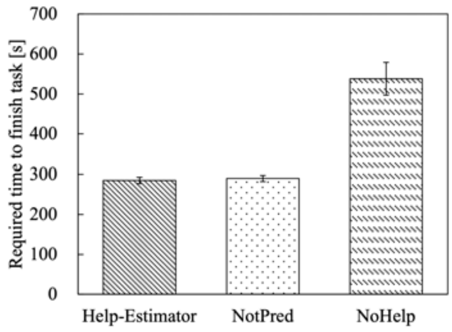

Fig. 12 Mean time to finish the task when the robot did not ask for help and in the Help-Estimator and NotPred conditions

7.4 Limitations

In this study, we used a simple artificial task in the preliminary case study and the experiment. We designed the simple task to enable the robot to estimate the remaining time for its task; we also assumed that the participants would easily estimate the remaining time for their task. In more complex or long-term tasks in which it is difficult for people to estimate their progress, they would behave in different ways from this study. Therefore, this study suffers from some limitations, and it is difficult to generalize its results to other tasks. Furthermore, Help-Estimator was based on several assumptions; that is, the robot assessed whether to ask for help at a 4-second frequency, and it did not ask for help for 30 seconds from the start of the task. Therefore, the applicability and generality of Help-Estimator in other domains is also limited.

The method of estimating the required time in this experiment was specific to the cleaning task. It will be necessary to develop other models of estimating the required time for the robot's task and the estimated time for the person's task when applying Help-Estimator to other cooperative tasks. In addition, the task here had to be one whose required time as a system could be quantitatively estimated in order to measure the time required for each task. However, people and robots sometimes engage in cooperative tasks that cannot be quantitatively estimated. Further research will be necessary to estimate the robot's time and the person's time even for such nonquantitative tasks.

We also focused only on the person's subjective time estimation according to our observations in the preliminary case study. Therefore, it is unknown whether other human factors, such as expertise, mood, trust, or engagement, could be effective for increasing a person's willingness to help a robot. To incorporate such factors, we will need to extend the case study and obtain further observations.

For the robot to estimate people's subjective estimated time for their task, Help-Estimator requires asking them to estimate the required time before starting the cooperative task. In the real world, however, it would be difficult to apply this style of initially setting multiple tasks, and it would not be realistic to ask a person the required time for a task. Thus, Help-Estimator should dynamically estimate the likelihood of a person helping through the interaction between the person and the robot.

In the experiment, the participants were instructed to work together with the robot to finish the task early, so they may have been biased toward being inclined to help. However, they followed the instructions during both experimental conditions (Help-Estimator and NotPred), and they were influenced by this bias at the same level under both conditions. In addition, the order of the conditions was counterbalanced. In this study, we only controlled the factor of whether the robot considered the participant's subjective time estimation when it asked for help. Therefore, other internal factors were balanced between the conditions, and the experiment was a reasonable one to verify the effect of Help-Estimator. On the other hand, to investigate the effects of other internal factors, the instructions will need to be redesigned.

8 Conclusion

In this paper, we focused on a person's subjective estimation of the time required for her or his individual task as part of a cooperative task with a robot. Our experimental results showed that the robot could obtain more help from the participants and was preferred by them when it asked for help by considering the person' s subjective time estimation.

In our future work, we will need to improve the accuracy of the robot's prediction of the estimated time in order to receive more help from people. In addition, the Help-Estimator system should update the estimation when a person does not help the robot. We should also reduce the estimation error of Help-Estimator through more interactions with people.

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Conflict of interest The authors declare that they have no conflict of interest.

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