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Efficiency Analysis in a Collaborative Task with Reciprocal Haptic Feedback

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Abstract— **Although it is reported in the literature that haptic feedback leads to improved performance in kinesthetic collaborative tasks, it has not been investigated so far whether this advantage is accompanied by a higher physical workload. This paper is an initial effort to examine efficiency in haptic interaction: We relate physical effort to a performance outcome in a virtual pursuit tracking task. An experimental study is conducted to compare efficiency in a collaborative mutual haptic feedback condition to three control conditions, where participants either acted alone or collaboratively without haptic feedback from the partner. Results show that reciprocal haptic feedback does not improve efficiency, although participants' performance was generally improved when doing the task with a partner, relative to executing it alone. This is due to the greater effort associated with physical connection between partners. However, the effort is more fairly distributed between partners when haptic feedback from the partner is provided. Haptic feedback may be more efficient when the amount of necessary communication between partners increases compared to the task studied here.**

I. INTRODUCTION

In addition to their application in pure industrial settings, nowadays robots are also introduced as human partners. They interact with humans to extend the human workspace to dangerous or inaccessible environments (telepresence), to assist as autonomous helpers in a broad range of tasks, and to enhance training as well as rehabilitation in real and virtual environments. Interaction is generally defined as the "relationship between two or more systems [...] that results in mutual or reciprocal influence" [16]. When physical contact between the two systems (partners) is given, interaction takes place via the haptic channel. It is based on the exchange of force and position signals between partners and hence, the communication of a shared trajectory.

We are far from knowing how to model haptic humam-human interaction (HHI). Consequently, substituting for one of the partners with a technical system or defining an adequate assistance strategy to be applied by the robot, as required for some of the above mentioned applications, is very challenging. This paper aims to enhance knowledge on HHI in particular by seeking measures that are representative of interaction with the ultimate goal of transferring the obtained knowledge to human-robot interaction (HRI).

In our opinion, research on interaction with haptic feedback can profit from an efficiency measure because it helps to investigate if and under which conditions the interaction partners benefit from mutual haptic feedback: when does their **performance** increase taking into account the related **costs**?

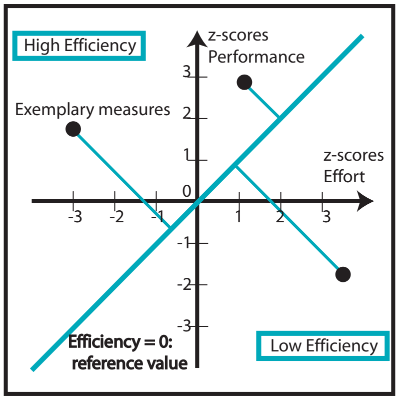

Fig. 1: Efficiency as function of performance and effort [4]. The calculation of efficiency is based on the distance between a measure and the reference line.

This question is of particular interest because haptic feedback is challenging from an engineering perspective: the involved bilateral energy exchange might easily lead to instabilities of the technical system. Especially, this is the case in teleoperation or virtual reality scenarios, where multiple human operators interact with each other to perform a common task [3] or in service robotics [10] when direct interaction of robots and humans is required. Hence, if haptic feedback is not always efficient, it might best be activated only in certain cases.

II. RELATED WORK

Efficiency is a measure dealt with in contexts such as usability [2], economy [5], (electrical) engineering [13], and cognitive science [12], [18]. One efficiency measure of particular relevance for our work is introduced in the field of human factors research. The measure is a linear function of effort (x-axis) and performance (y-axis) [12] as illustrated in Figure 1. The values are z-score standardized (M = 0, sd = 1) to take into account the different scales of the two measures.

Common to all efficiency definitions found in literature is that they contain two constructs: one describing the quality of behavior (output, effective power, effectiveness, performance) and the other relating to resources involved (input, costs, total power, effort, workload).

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To the best of our knowledge **efficiency in haptic collaboration** has not yet been addressed in experimental studies. However, as performance is part of the efficiency construct defined in the former section, below we report studies investigating performance in joint object manipulation tasks with haptic feedback.

In the literature, performance in haptic feedback conditions is typically described in relation to one of the following two control conditions:

- Visual feedback only: An interactive task is performed with visual feedback only [1], [15]. This can only be done in virtual or technically mediated environments.
- Single person: The behavior during interaction is compared to individual execution of the same task [7], [14].

All these studies examine performance, but only [14] measures forces, which can be interpreted as physical effort. However, the relation between effort and performance is not generally considered.

III. RESEARCH QUESTIONS

The goal of the present study is to answer the following research questions for interaction of low complexity with reciprocal haptic feedback:

1) Is haptic feedback efficient in low-level collaboration trials compared with control conditions of individual performance and interaction without haptic feedback of the partner?
2) How is efficiency distributed between partners comparing trials with and without mutual haptic feedback?

IV. METHOD

Here we consider haptic interaction as a negotiation regarding the trajectory of a jointly carried object. In contrast to the object trajectory resulting from negotiation, planned individual (desired) trajectories are cognitive constructs which are not accessible for measurement. A key feature of the tracking task paradigm is that it externalizes these latent desired trajectories by means of the tracking path. The path serves to instruct the participants about the desired trajectories, so the deviation from the desired and the actual shared trajectory can be objectively defined and studied.

A. Experimental Setup

In the present pursuit tracking task, participants were asked to move a virtual mass visually presented by a cursor along a given reference path (see Fig. 2). As introduced in more detail in Sec. IV-B, four different conditions, two single and two interaction conditions, were defined. All four conditions have in common that the reference path was designed as a random sequence of the same components (triangles, curves, straight lines, jumps). It was displayed as a white line on two black screens (both showing the same scene). As the path scrolled down the screen with a constant velocity of 15 mm/s, participants were asked to follow it, as accurately as possible, with the red cursor. One trial took 161 s. The horizontal position of the cursor renders the resultant position of the haptic interfaces the participants used to interact with each other.

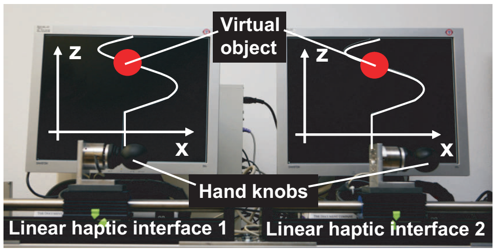


Fig. 2: Experimental setup consisting of two linear haptic interfaces (linked by the virtual mass) and two screens with the graphical representation of the tracking path

These interfaces have one degree of freedom (1 DOF) and allow movements along the x-axis. Each interface is equipped with a force sensor, hand knob and linear actuator. Their control is implemented in Matlab/Simulink and executed on the Linux Real Time Application Interface RTAI. The graphical representation of the path runs on another computer and communication is realized by an UDP connection in a local area network.

The control of the haptic interfaces is designed to model a jointly carried virtual object. The virtual object is defined as a single mass only and its dynamics is given by:

$$f_{sum}(t) = f_1(t) + f_2(t) = m\ddot{x}_{vo}(t) \tag{1}$$

where f_{sum} is the sum of the forces applied by the participant/s which can be measured separately, m is the virtual mass and $\ddot{x}_{vo}$ is the acceleration of the virtual object and, hence, of the linear haptic interfaces. The corresponding transfer function in the Laplace domain

$$G(s)_{vo} = \frac{X_{vo}(s)}{F_{sum}(s)} = \frac{1}{ms^2} \tag{2}$$

is realized by a position-based admittance control (for more details please refer to our previous work [6]).

B. Experimental design

In order to investigate the efficiency of haptic feedback in a joint pursuit tracking task, a condition with haptic feedback from the partner and three different control conditions were examined. The resulting four conditions are described below:

1) Vision-haptic condition (VH): The partners get identical visual feedback of the tracking scenario and are also connected via the haptic channel. In addition to feeling the mass of the virtual object ($m = 20$ kg), they also feel the forces applied to the object by their partner. This is achieved by introducing a virtual rigid connection between the interacting partners, i.e. $x_{vo}(t) = x_1(t) = x_2(t)$. The virtual object (cursor) position is determined by transforming (2) into time-domain and solving for $x_{vo}(t)$

$$x_{vo}(t) = f_{sum}(t) * g_{vo}(t) \tag{3}$$

with $g_{vo}(t)$ the inverse Laplace transform of $G_{vo}(s)$.

2) Vision condition (V): Again, visual feedback is provided. The mass ($m = 20$ kg) of the cursor is divided into two parts, such that each partner has to carry 10 kg, which presents an equal sharing of the workload. The participants feel only the weight of the mass but not the forces applied by their partner. The cursor position is defined as the mean of the two individual device positions

$$x_{vo}(t) = (x_1(t) + x_2(t))/2. \tag{4}$$

Each partner can only infer what the other is doing from inconsistencies between his or her own movements and the resulting cursor position.

3) Alone condition with full mass (AF): The participant executes the task alone. He/she has to move the same virtual mass in the same way as two participants do in the VH trials ($m = 20$ kg).

4) Alone condition with half mass (AH): The participant executes the task alone. He/she has to move only $m = 10$ kg cursor mass, which is identical to the workload of an individual in an interaction task with equally shared workload or the workload in the vision condition.

We randomized the sequence in which the conditions were presented to the participants. For a further standardization of the test situation we undertook the following arrangements: a wall was placed between the two participants so they did not gain visual information about the movements of their partner; participants used their right hand to perform the task (all of the participants are right-handed); participants were not allowed to speak to each other during the experiment; white noise was played on headphones worn by participants, such that the noise of the moving haptic interfaces would not distract; and the position (left or right seat) was randomized with the order of experimental condition.

Participants were instructed to keep the cursor on the path. They were informed about each condition beforehand. In addition, they knew that the first curve of the tracking path was for practice and would be excluded from the analysis.

C. Participants

The tracking task was conducted by 24 participants forming six groups of four persons each. Participants interacted in accordance with a round robin design [11], such that each performed in partnership with each of the group members (V, VH) as well as alone (AF, AH). In the results presented here, due to the independent error assumptions in inference statistical analyses [11], all participants were randomly assigned to a dyad, and only independent dyads were considered. Thus in this analysis, 24 participants (age mean: 27.6, std. deviation: 2.5) forming 12 independent mixed-gender dyads are involved. We consider the task intuitive enough so preknowledge on haptic devices is not influencing the task. To be sure to eliminate this factor, we chose a repeated measurement design.

D. Data Analysis

As stated in Sec. II, the two components of an efficiency measure are performance and effort measures. Accordingly, those are introduced in the following section and are later combined to create an efficiency measure. This efficiency measure then helps to compare efficiency:

1) between dyads in a given sample
2) between environmental conditions such as different partners, different displays, different tasks etc.
3) between two partners of a dyad

In the present experiment, we consider comparisons 2) and 3).

1) Performance Measure: Performance measures are highly task-related. The root-mean-square error (*RMS*), time-on-target and task-completion time are possible performance measures in a tracking task scenario [17]. Depending on the given task, more specialized performance measures might be suitable. In our analysis we chose to use the *RMS* based on the displacement between the desired position x_{ref} and the actual position x_{vo} because the trial duration was fixed in our experiment, compare [6].

2) Effort Measure: In the field of haptic interaction, cognitive or physical resources have to be further distinguished. In the current paper we focus exclusively on physical effort. Physical effort is directly related to forces and motion (in the following we always refer to physical measures if not stated otherwise). As a result, the effort measure is based on mechanical power/energy.

The energy flow from partner 1 to the environment is defined as follows

$$P_1 = f_{h1}\dot{x}_{vo} \tag{5}$$

with f_{h1} the applied force and $\dot{x}_{vo}$ the velocity of the virtual object. The energy flow between partner 2 and the environment is defined correspondingly. It is intuitive that a higher energy flow relates to a higher physical effort. Furthermore, physical effort for the operator is involved not only in injecting mechanical energy to the system (e.g. acceleration of a mass), but also dissipating energy from it (e.g. deceleration of a mass). For this reason, the effort measure on the dyadic level (index d) is defined as the mean *absolute* power

$$MAP_d = MAP_1 + MAP_2 = \frac{1}{N}\sum_{k=1}^{N}|P_{1,k}| + \sum_{k=1}^{N}|P_{2,k}| \tag{6}$$

where $P_{1,k}$ and $P_{2,k}$ is the energy flow at the respective interfaces at a given time step k ($k = 1\ldots N$).

This effort measure allows for a comparison between haptic, non-haptic and alone conditions. In the two alone conditions the partner effort is defined as zero. Furthermore, we separate two types of forces that can be applied by the participants: a) external forces f^E which are responsible for object motions and b) interaction forces f^I, which result from participants pushing against or pulling away from each other. These force measures are not part of the efficiency measure in the current paper, but will help to explain efficiency related results.

3) Efficiency Measure: The efficiency measure is based on the distance efficiency measure from [4], [12] introduced in section II and the performance and effort measure introduced previously.

It must be noted that in the following efficiency definition, high performance values represent good performance. Therefore, the *RMS* is transformed as follows:

$$B = 1 - \frac{RMS}{RMS_{max}} \tag{7}$$

where $RMS_{max} = 0.0055$ m is the maximum *RMS* found in the given data set.

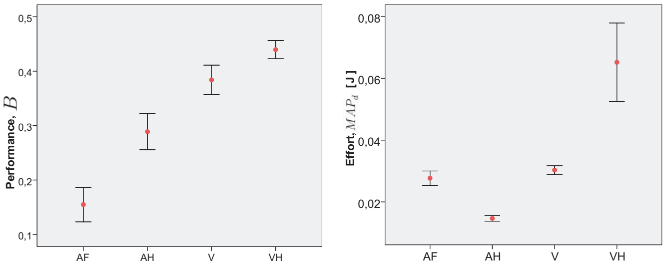
This results in the efficiency measure:

$$\Lambda_d = \frac{Z(B) - Z(MAP_d)}{\sqrt{2}} \tag{8}$$

The z-standardization, $Z(B)$ and $Z(MAP_d)$, takes place over all experimental conditions. Note, that the index "d" relates to the fact that we consider the overall system (dyad). This is also true if we measure efficiency in alone trials where one participant represents the overall-system.

When we approach the efficiency Λ_i of a single partner, efficiency has to be defined on an individual level instead of on the dyadic level: either the performance or effort measure has to be described individually for both partners. Due to the fact that performance in haptic tasks is mainly described in relation to the involved object and hence, is the same for both partners, it must be the the effort measure that is individually described. Consequently, differences between partners with respect to efficiency will be due to effort. The individual efficiency Λ_i is based on MAP_1 or MAP_2 and the dyadic *RMS*. The z-transformation was conducted separately for the two partners but across the data from both interactive conditions.

It is not possible to approach the difference or similarity in efficiency of individual dyad members with the Pearson correlation measure. This is the case because the two dyad members are exchangeable. Exchangeability here means that there is no clear role distribution by which the individuals can be distinguished. For example, if we develop our data sheet for correlations, we build two columns, one for a certain variable of each partner. It is arbitrary if we allocate a particular individually measured efficiency to the column "Partner A" or "Partner B". In this way various possible groups of data can be built, leading to different correlations. One way to overcome this problem is the pairwise intraclass correlation [8], [11], which can be based on the double entry method: all possible within-group pairings of scores are built before calculating the correlation on this dataset. For dyads, that means that the individual measures of a couple are entered in the dataset in both possible configurations. In this way the relation between the individual variables can be determined by a Pearson product-moment correlation. Based on this method we calculate the intraclass correlations by taking care of the adjusted significance level due to the doubled data entries [8].



(a) Performance measure B (b) Effort measure MAP_d

Fig. 3: Comparison between the four tracking conditions AF (alone with full mass), AH (alone with half mass), V (visual interactive trial), VH (visual/haptic interactive trial): mean and standard error

V. RESULTS AND DISCUSSION

A. Efficiency in the four conditions

As shown in Fig. 3(left), performance was better in interactive trials than in individual trials. Hence, even in a haptic collaboration task, which can be performed alone, the participants profited from interaction with a partner. This is true even compared with the AH condition, where the mass was halved, thus instantiating optimal mass sharing between two partners. Compared to the visual feedback only condition, the haptic feedback descriptively leads to a further improvement of performance in the interactive task.

The four experimental conditions differ with respect to the effort measure, see Fig. 3(right). It must be noted that we analyzed the overall effort here, meaning the effort applied by the system to move the cursor, independent of whether this system includes one or two humans. The AH condition elicits lower effort compared to the other conditions, which is due to the fact, that here the overall cursor mass is halved (10 kg) compared to all other conditions. No difference is found between the effort in V and the effort in AF. The mass which has to be moved by the system (one or two humans) is equal in both conditions. Therefore, we conclude that the effort depends on the mass rather than the interaction, when there is no reciprocal haptic feedback provided. In the VH condition a mass of 20 kg was implemented. Hence, the effort required to move the mass along the path is the same as in the AF condition. But, here the effort is highest of all conditions. Therefore, we infer that here additional effort due to interaction and not only mass plays a role: Interactive forces are involved aside from the necessary external forces. A comparison of two effort measures based on those force types is illustrated in Fig. 5; descriptive statistics can be found in Table II. The large standard error suggests that the amount of interactive force varies between dyads.

In Fig. 4 the results for the efficiency analysis are plotted. A one-factorial, repeated-measurement ANOVA was conducted for the efficiency measure. Due to a lack of sphericity, the ANOVA was Greenhouse-Geisser corrected (F(1.935, 21.281)= 6.671; p= .006; η^2= .378)). Because the

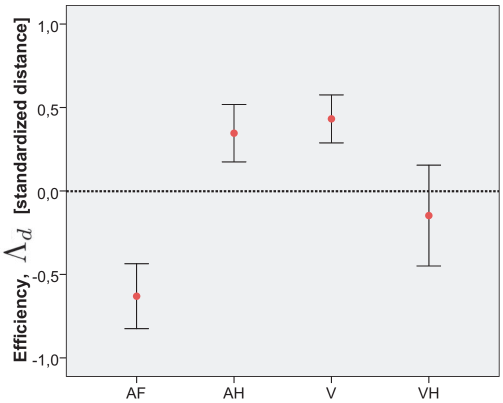


Fig. 4: Efficiency expressed in Λ_d. Comparison between the four tracking conditions: mean and standard errors. The zero line expresses the overall mean across all conditions (abbreviations as in Fig. 3) as a reference efficiency value (cf. Figure 1)

TABLE I: Pairwise efficiency Λ_d comparisons betwen conditions: p-values. Significant values at the 0.05 level are marked with *

condition	AF	AH	V	VH
AF	-	0.007*	0.005*	1.000
AH	0.007*	-	1.000	1.000
V	0.005*	1.000	-	0.290
VH	1.000	1.000	0.290	-

conditions together had a significant effect on efficiency, pairwise comparisons were executed with Bonferroni adjusted post-hoc tests; see Table I. Efficiency is significantly higher in the V and AH condition compared to AF. Two people interacting with visual feedback and 20 kg mass only are as efficient in this task as one person performing with half the mass. There are no advantages of interaction here. This is because the efficiency measure reflects the fact that V costs higher effort but leads to improved performance compared to AH. The interactive haptic feedback condition does not differ significantly from any other condition, due to the high standard error. This means that haptic feedback interaction generally neither improves nor worsens efficiency in the given collaboration. There may, however, be factors other than feedback influencing efficiency here. One is addressed in the following section.

TABLE II: Mean and standard error of dyadic external and interaction forces [N] for the two interaction conditions V and VH

condition	mean f^E	std. error f^E	mean f^I	std. error f^I
V	1.1022	0.03895	0.1301	0.01400
VH	1.2037	0.04778	1.6593	0.53103

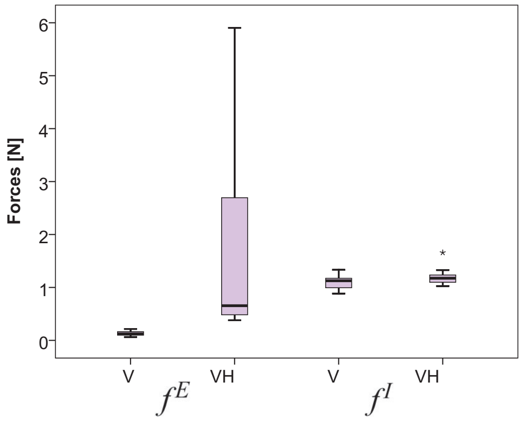


Fig. 5: Box-and-whisker plots comparing external and interaction forces for the two interaction conditions V and VH (abbreviations as in Fig. 3). Wheras the interaction forces are similar in the two conditions, mutual haptic feedback leads to increased external forces compared to V.

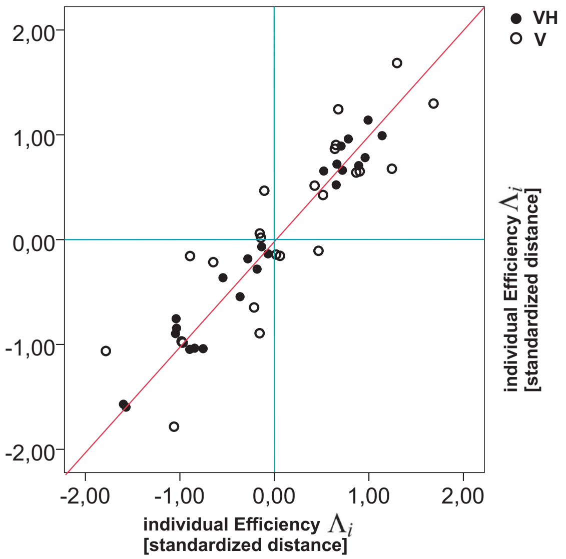


Fig. 6: Each dyad is presented twice by a dot (based on the double entry method). The closer to the diagonal the dots lie, the more similar are the individual efficiencies (Λ_i) between partners within dyads: With haptic mutual haptic feedback the individual efficiency of the partners is more similar.

B. Within-Dyad Efficiency

In the aforementioned results we analyzed efficiency on a dyadic level. Now, we will examine efficiency on an individual level and compare differences or similarities in this measure between the two partners. The intraclass correlations on individual efficiency values within a dyad for the two interactive conditions are V: r = 0.867; p(one-tailed)= .002 and VH: r = 0.983; p(one-tailed)= .000. The two intraclass correlations for the V and VH condition differ significantly from each other, when testing the hypothesis of equality with Fisher z-transformed values as proposed by [11] (z = 2.3674; p(two-tailed) = 0.0182).

In Fig. 6, the efficiency measure of each dyad member is plotted in relation to the other. Each dyad is entered twice, according to the two orders in the double-entry data set [9]. The closer the dots to the 45° diagonal, the more similar the dyad members are. The values of the intraclass correlations show that the efficiency of the two partners is generally very similar in both feedback conditions. The performance measures, on which these efficiency values are based, are equal for both partners, because performance is measured on the dyadic level (IV-D.3); accordingly, efficiency differs between individuals within a dyad only by effort. Hence, we conclude that similarity between partners is due to comparable individual effort during task execution. The difference in correlations between the V and VH conditions reflects finally that the workload distribution between partners is more equitable in the VH condition.

VI. CONCLUSION AND FUTURE WORK

To summarize our contributions, we introduced an efficiency measure which is appropriate to compare the efficiency between different conditions in a haptic task, and between the two interacting partners. Experimental data from four tracking task conditions were compared with respect to this measure: Participants acted alone with full or reduced mass, and participants acted in interaction with a partner while receiving either only visual and haptic feedback from the object or in addition haptic feedback from the partner.

The mutual haptic feedback condition required more effort on a dyadic level than the vision feedback condition. This is because the partners apply interactive forces in addition to the forces necessary to move the object. Therefore, haptic feedback cannot be considered efficient in the present interaction task. Compared to doing the task alone with full mass, the vision-only interactive condition led to increased efficiency. However, when individuals performed in a half-mass condition, representing shared workload, their efficiency was equal to the vision-only interactive condition. Thus, the overall efficiency was influenced by the mass of the carried object, rather than by the fact that the task was completed with a partner versus without.

The high variability in efficiency when haptic feedback is given, due to the different amount of interactive forces per dyad, leads to the conclusion that haptic feedback might not always be of advantage. This is especially true when taking into account the challenges from the engineering perspective. However, haptic feedback leads to a fairer effort distribution between the partners within a dyad compared to a vision-only condition.

In future, we will analyze more complex collaborative tasks, based on the assumption that with a higher need for communication between partners haptic feedback will lead to increased efficiency due to this feedback channel. Furthermore, we will investigate the forces exchanged between partners (especially interactive forces) over time to get further insights into haptic collaboration.

VII. ACKNOWLEDGMENTS

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